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Green-Ampt infiltration model parameter determination using SCS curve number (CN) and soil texture class, and application to the SCS runoff model

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Green-Ampt Infiltration Model Parameter Determination Using SCS Curve Number (CN) and Soil Texture Class, and Application to the SCS Runoff Model.

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ABSTRACT

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The U.S. Department of Agriculture (USDA) Soil Conservation Service Curve Number (SCS CN) method is a simple and widely popular technique of estimation of direct runoff volume for design and natural rainfall events in small watersheds. The SCS CN procedure is incorporated into such computer programs as TR-20 and TR-55. Although the method reliably predicts 24-hr runoff volume, the predicted distribution of runoff during a storm event is not realistic. This shortcoming of the SCS CN method is due to weakness in the infiltration concept of the method. Use of a physically realistic and distributed Green-Ampt infiltration model can significantly improve the SCS CN method.

The purposes of the present investigation were to incorporate the Green-Ampt infiltration model into the SCS CN method and to explore its advantages over the Curve Number infiltration model. As a result, a procedure of evaluating the Green-Ampt parameters from the SCS Curve Numbers for various soil texture classes was developed. The comparison of peak discharge estimation by both models for various rainfall depths and time of concentrations showed a divergence in predictions of up to 77 percent for low runoff potential soils.

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CHAPTER 1

INTRODUCTION

Estimation of runoff distribution and volume is a critical point in engineering design of hydraulic structures, erosion estimations, and environmental impact evaluation. In the late forties-early fifties the SCS Curve Number method was developed for the purpose of estimating direct runoff from ungaged small watersheds, and to determine the effects of changes in land treatment and use. The method gained popularity among engineers and hydrologists in both government and the private sector because of its simplicity and well established procedure. However, the Curve Number method is not the most conceptually reliable model and has various shortcomings, which are continuously discussed in the literature. Considering the great likelihood of the continued use of the model in the future, the SCS Curve Number method is in need of update and improvement.

The SCS CN method infiltration concept is one of the primary objects of criticism. As has been pointed out in various publications, the infiltration model used in the SCS CN method is in disagreement with major infiltration theories and, as a result, cannot realistically estimate the infiltration distribution during a storm event, and consequently, misjudges predictions in peak discharge. One possible way to improve the Curve Number method is to include some physically realistic infiltration model. The National Resources Conservation Service (NRCS), formally the Soil Conservation Service (SCS) espouses the Green-Ampt infiltration model as one such possibility (Miller and Cronshey, 1989).

The Green-Ampt infiltration equation is derived from the application of Darcy's law to unsaturated flow in a homogeneous soil profile. Though there are no extensive data available for evaluating the equation parameters, they are physically based and can be related to soil properties. Rawls and Brakensiek (1982, 1983, and 1986) developed the method of estimating the Green-Ampt parameters from the USDA soil survey data. This method allows the application of the Green-Ampt infiltration model to any watershed for which soil survey data exists. The authors estimated and introduced the sets of average Green-Ampt parameters for 11 Soil Texture Classes and Horizons, analyzed natural runoff events for different soil texture classes, and made comparisons of direct runoff predictions by the Green-Ampt and SCS Curve Number models with respect to measured runoff. The authors did not quantify the comparison results or establish any relationship between the Green-Ampt parameters and the SCS curve numbers. The importance of having such a relationship is found in the ability to estimate infiltration by the Green-Ampt model within the SCS CN method.

Several comparison studies were made to investigate differences in the predictions of runoff and peak discharge volumes given by both models. Two publications (Van Mullem [1989] and Nearing et al. [1996]) introduced empirical relationships between the Green-Ampt hydraulic conductivity and curve numbers. These equations are rather specific, derived under certain conditions and not proved to be applicable as a general method of infiltration calculation within the SCS CN procedure framework.

As distinct from other investigations, the present project examines the differences in predicted by the Green-Ampt and the SCS CN infiltration model's runoff distributions, when using the standard SCS Curve Number method as a design tool on ungaged watersheds. The effect of precipitation depth and time of concentration on both model's performance were analyzed and a new approach to compare infiltration models is proposed. As a result of this study, and in order to support the use of the Green-Ampt infiltration model within the SCS CN method, a procedure for determining the Green-Ampt parameters which produce the same direct runoff as that obtained by the SCS CN method is provided. This procedure contains a developed series of plots, which define the relationship between the Green-Ampt hydraulic conductivity and the SCS curve numbers for various rainfall depths and soil textures.

Goal and Objectives

The goal of the present study is to support the use of the Green-Ampt model in place of the SCS CN infiltration model within the popular SCS CN method in order to improve the aforementioned SCS CN method.

The objectives of the present project are:

1. To apply both infiltration models to various storm events of Type II standard rainfall distribution over a standardized watershed of area 1 km^2.
2. To establish a relationship between the Green-Ampt parameters and SCS curve numbers, which will produce the same amount of runoff.
3. To obtain detailed runoff hydrographs from unit hydrographs of different durations according to the standard SCS CN procedure.
4. To demonstrate advantages of the Green-Ampt model performance over the SCS CN infiltration model by comparing predictions of accumulated infiltration and runoff distribution.

CHAPTER 2

LITERATURE REVIEW

2.1 SCS CN Method

The Soil Conservation Service (SCS) Curve Number method had been developed based on extensive field studies and soil condition records across the United States. A number of investigators had been involved in examining and analyzing the relationship between rainfall and direct runoff. In the mid 1930's, a number of experimental watersheds of various drainage areas were established at different locations to provide rainfall-runoff data. Additionally, infiltrometer runs were made using thousands of sprinkling-type infiltrometers. The plots, which were used to obtain data had varying sizes: some 6 feet wide by multiples of 12 feet long; and some 12 inches by 30 inches. L. K. Sherman (1949) was the first to introduce the idea of plotting direct runoff volumes versus rainfall depth. V. Mockus (1949) investigated the estimation of runoff from data on soils, landuse, antecedent rainfall, rainfall depth and distribution, data of storm, and temperature. R. Andrews (1954), by analyzing data from infiltrometers plots, developed a graphical procedure to estimate runoff from rainfall according to soil textures, type and amount of cover and conservation measures. The work of Mockus and Andrews has became a basis for the SCS Curve Number method as a means of estimating direct runoff (Miller and Cronshey, 1989).

The general observations from the storm event study were:

1. Runoff does not start immediately. There is a certain amount of rainfall that must first satisfy interception, depression storage, and initial infiltration. This part of precipitation is referred to as initial abstraction, I_a.
2. After initial abstraction is satisfied, runoff occurs and the difference between rainfall depth, P, and runoff volume, Q, is the loss due only to infiltration.
3. The infiltration loss is actual retention, F, a value that can grow with increasing rainfall to a maximum possible retention, S.

The Figure 2.1 represents the graphical relationship of the above listed parameters.

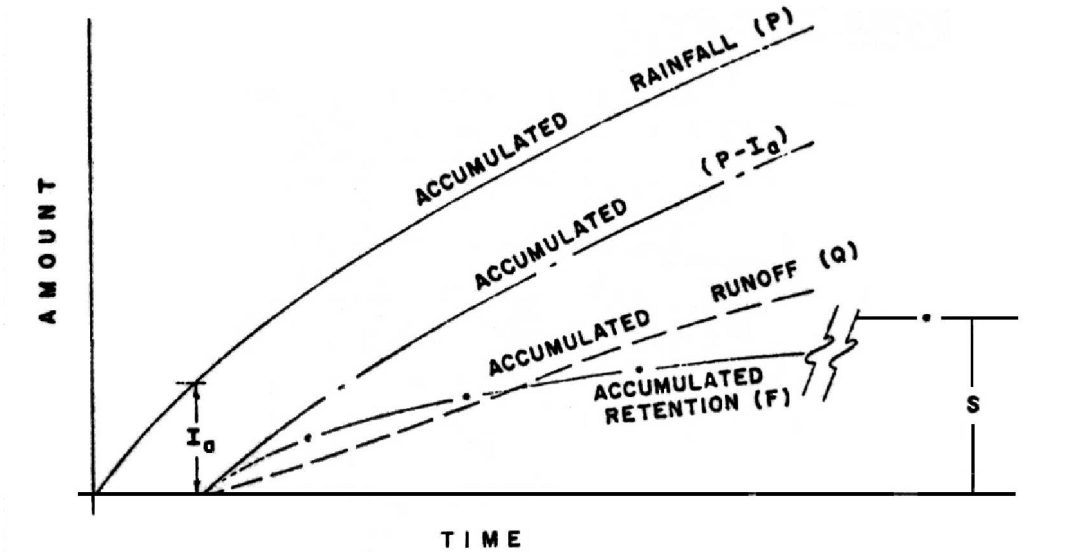

Figure 2.1 Schematic relationship of parameters in SCS CN method (Rallison and Miller, 1981)

The observations lead to the assumption that was expressed mathematically as:

$$\frac{F}{S}=\frac{Q}{P-I_a} \qquad \text{for } P > I_a \tag{2.1}$$

where : S – potential maximum retention;

F – actual retention;

Q – actual runoff;

I_a – initial abstractions;

P – potential maximum runoff that is equal to the total precipitation.

Earlier editions of the National Engineering Handbook (NEH-4) use two notations for the potential maximum retention: S and S', with an established relationship between them:

$$S = S' + I_a \qquad \text{or} \qquad S' = S - I_a$$

Such a use of two different notations for the maximum potential infiltration involved in equation 2.1 leads to a discussion among hydrologists (Chen [1981], McCuen [1982], Westphal [1982], Hjelmfelt [1991]). The Soil Conservation Service (SCS, 1985) in their 1985 edition of NEH-4, accepted a definition of S which includes the initial abstractions, I_a.

Based on data from various parts of country, the relationship between I_a and S was developed as:

$$I_a = \lambda * S \tag{2.2}$$

where: λ = initial abstraction ratio.

Fifty percent of the observed data for initial abstraction ratio lay in the interval between 0.095 and 0.38 (SCS, 1985). The single value of 0.2 was selected as the design value for λ. A number of studies demonstrate and state that λ should be assigned some other value, or be left as a variable. The investigation performed by A. Plummer and D. E. Woodward (web source, unpublished) implies that there is no linear relationship between the runoff curve numbers for two different I_a conditions. Any other relationship between I_a and S would require a different set of runoff curve numbers and more than simple changes in the runoff equation.

Considering the fact that the actual infiltration, F, is the difference between effective precipitation and actual runoff (P-Q), and performing a simple mathematical transformation, equation 2.1 becomes the SCS direct runoff estimation equation:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{2.3}$$

In the SCS CN procedure, for convenience and simplification, parameter S was transformed into a new dimensionless parameter CN “Curve Number”, that represents the average of median site values for soil, cover, and hydrological conditions:

$$CN = \frac{1000R}{S + 10R} \tag{2.4}$$

The pair of arbitrarily chosen constants 1000 and 10 has the same units as a potential retention, *S*. The conversion coefficient, *R*, is equal to unity if *S* is in inches, and equal to 2.54 cm/in if *S* is presented in centimeters. For potential retention which varies within limits from 0 to infinity, the curve number, *CN*, lays in the theoretical range from 0 (Q = 0) to 100 (Q = P). The practical range, however, is found from 55 to 95 (Hawkins, 1998). A verification study performed by Bales and Betson (1981) proved a high correlation of the *CN* and land use, and a certain relation of the *CN* to soil measures. The investigators also found a storm hydrograph to be very sensitive to the curve number. The curve numbers for different locations and moisture conditions can be obtained from the SCS hydrology handbook (SCS, 1986). The latter contains tables that allow one to select a curve number for particular soil type, land use, and management. For example, a golf course of fair condition (grass cover 50%-75%) and with soil of hydrologic group D, has *CN* of 84. Alternately, a wooded area of good hydrologic condition and of hydrologic soil B has *CN*=55.

Antecedent moisture condition (AMC) is used in the CN method in order to make an adjustment in the curve number due to variations in some initial conditions, such as soil moisture, infiltration, evaporation, temperature, etc. The AMC II represents the benchmark situation and corresponds to the standard curve number. AMC I and AMC III represent the "dry" and "wet" conditions, respectively, and correspond to the low and high curve number values in the data scatter. Adjustment for AMC I and AMC III is based on the total precipitation in the previous five days (Ponce, 1996).

All soils in the United States have been divided into four Hydrologic Soil Groups. These groups were defined as A, B, C, D, and dual groups A/D, B/D and C/D. Group A has a low runoff potential and under the wet condition has a high infiltration rate (f>0.3 in/hr). Group B has the same features as group A, except with a moderate infiltration rate (0.15<f<0.3). Group C is defined as soils with low infiltration rates (0.05<f<0.15) and an impermeable layer that prevents the downward movement of water. Soils with a high runoff potential and a very slow infiltration rate (0<f<0.05) were assigned to group D. Dual group soils have a shallow depth to a permanent water table which is the sole criterion for placing them into hydrologic group D. Under well-drained condition these soils would belong to a different hydrologic group A, B, or C.

The SCS CN procedure for estimation of direct runoff is fully described in Chapter 10, Section 4, of the Engineering Handbook (NEH-4). Generally, it follows four steps:

1. Determination of the soil group (Table 9.1, NEH-4, 1972).
2. Evaluation of the five-day antecedent moisture condition (Table 4.2, NEH-4, 1972).
3. Based on the first two steps, and upon consideration of land cover and treatment, the actual runoff curve number is decided (Table 10.1, NEH-4, 1972).
4. Using Figure 10.1 and Equation 10.10 from the NEH-4, direct runoff for each day of precipitation is determined.

The features of the CN method include limitations on runoff depth, Q, lying in the range between zero and the precipitation amount, P, and actual retention, F, asymptotically approaching the maximum potential retention, S. The method is based on infiltration losses, which is the major abstraction in storm direct runoff determination. Based on the concept underlying the creation of the CN method, losses due to evaporation and evapotranspiration are not considered to be significant in a single design storm and the method does not account for such abstractions. Originally developed as a lumped model, the Curve Number method combines spatial and temporal variations in the total infiltration depth over a watershed area for a given precipitation depth (Ponce and Hawkins, 1996). The CN lumped model does not represent instantaneous infiltration rates but rather converts a storm depth into direct runoff.

As pointed out by R. Rallison and N. Miller (1981), the SCS CN method was developed to predict impacts of land use and treatment changes on direct runoff for ungaged areas of small (less than 25 km^2) watersheds. The procedure is reliable if used to solve problems for which it was designed. The CN technique is well established and used by numerous federal, state, and local agencies. Due to the simplicity of the described procedure, and the involvement of just a few watershed characteristics, the SCS CN method has for almost half a century remained the most widely used procedure to estimate storm runoff volumes, peak discharges, and hydrograph development.

Because of its popularity and wide use throughout the United States, The SCS Curve Number method is an object of a growing number of research publications. Numerous investigations, whose object is to improve the method and its procedure, have been carried out (Simanton et al. [1996], Mack [1995], Steenhuis et al. [1995], Hawkins [1993], Hjelmfelt [1991], Bosznay [1989] and many others).

2.2 Infiltration Formula by Curve Number Method

Given this extensive research, many questions and criticisms have arisen regarding the method's underlying concepts, particularly its representation of infiltration rate. There were many attempts made to support the SCS CN model as a representation of infiltration rate. Smith (1976) presented the infiltration rate implicit equation for constant rainfall rate, an equation which was derived by differentiation of the basic curve number equation:

$$f = \left(\frac{S}{P + 0.8S} \right)^2 i \; ; \qquad P > I_a \tag{2.5}$$

where: f = infiltration rate,

i = rainfall rate.

Figure 2.2 illustrates the dimensionless expression of infiltration rate as it is derived from the SCS rainfall runoff equation and standardized on f / i and P / S.

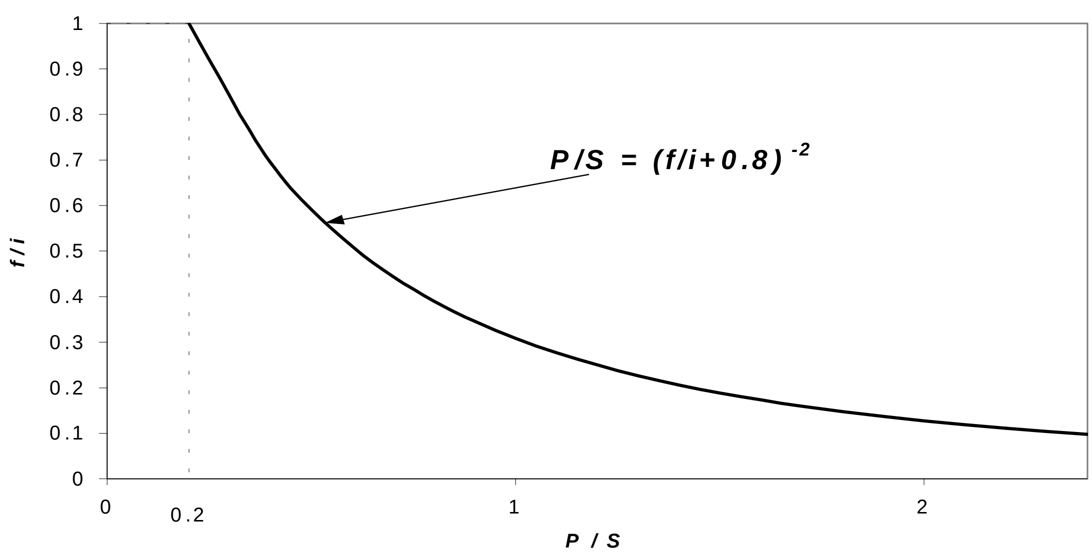

Figure 2.2 Dimensionless expression of infiltration rate from the SCS equation (Hawkins, 1978)

Smith's conclusion (Smith, 1978a) is that the SCS formula represents a physically incorrect relationship between precipitation rate and infiltration rate. Smith (1978) points out two major disagreements with other infiltration theories. First, that infiltration before runoff starts has a uniform value I_a in the SCS CN method. Second, according to the SCS method, the infiltration rate, after runoff starts, depends on rainfall rate. Figure 2.3 shows infiltration rates and rainfall rates for 5 inch, 24-hr Type II distribution design storm defined by the CN method.

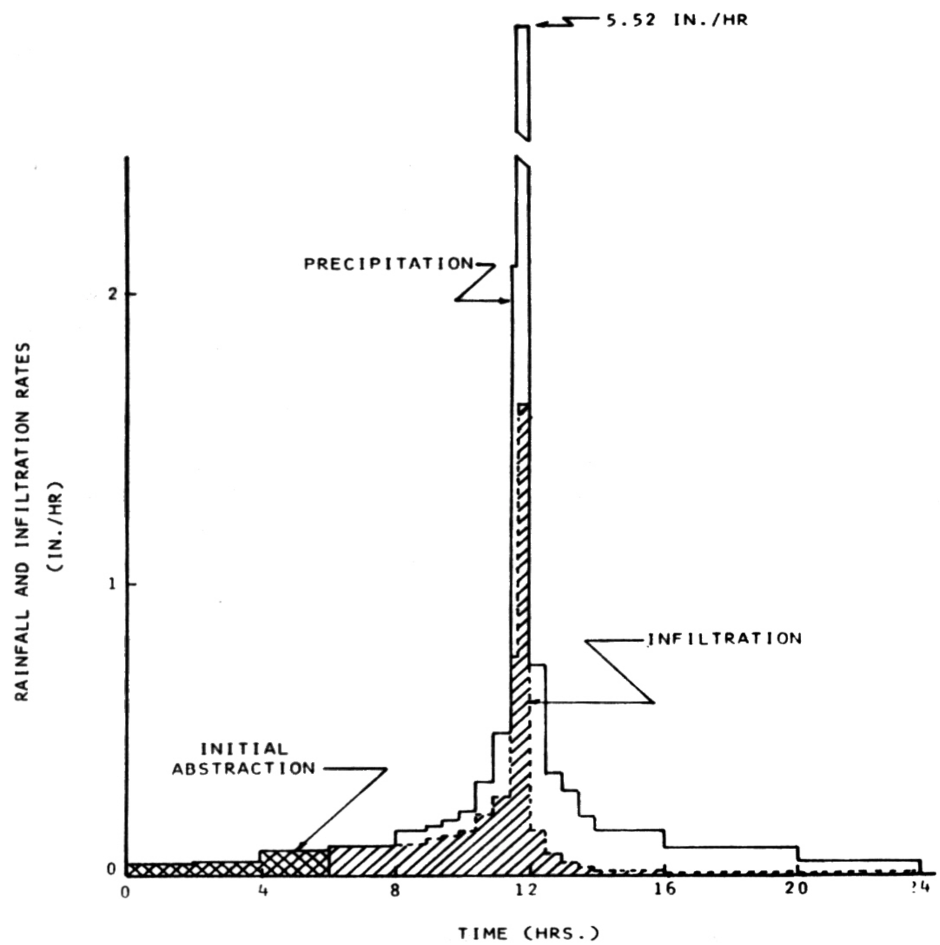

Figure 2.3 Example of rainfall and infiltration distributions by the SCS CN model for designed storm (Hjelmfelt, 1980).

In reality, however, the first phase is not a uniform value and the length of it depends on the rainfall rate and patterns, because the surface flux capacity, provided by the soils unsaturated capillary gradient, is larger than the precipitation rate. In the second phase, the rainfall rate surpasses the infiltration capacity and the infiltration rate is controlled only by the condition of the soil (Smith, 1978). The other effect of equation 2.5 is that the infiltration rate of constant intensity rainfall will decrease and approach zero instead of a residual constant rate, f_c. This predicts the effective precipitation at the very end of a storm of low intensity rainfall (Hjelmfelt, 1980). The proposal presented by Aron et al. (1977) states that equation 2.5 could realistically estimate infiltration rates for urban or rural watersheds because the time rates of infiltration are not as important as cumulative infiltration. Smith (1978) criticized this proposal because according to his experience "the simulation of infiltration response may be the most critical factor in correctly modeling surface water runoff".

Some other investigators (Chen [1982], Hjelmfelt [1980a, 1991]) also argue that the SCS “simple” infiltration equation does not agree with other infiltration theories. Attempts to relate the above equation (2.5) to the other infiltration equations were made by several studies. Hjelmfelt (1980) and Chen (1976) showed that for the particular case of constant rainfall rate and zero final continuous infiltration rate, the equation is similar to the Holtan-Overton equation. In order to introduce time relationship, Aron (1992) combined the SCS with Horton infiltration equations and obtained the modified SCS infiltration rate estimation that should be useful for intermittent storm events. Hawkins (1982) presented the interesting concept of a "lumped model" definition. Spatial and temporal uniformity of lumped models can be considered a spatial and temporal averaging. Developing such a concept, the author (Hawkins, 1982) derived a new method, which incorporates an equation of infiltration (loss) rate distribution due to spatial variability of the rainfall event within a watershed. However, one of the possible solutions to overcome the conceptual problems of the SCS CN infiltration model is to incorporate some other infiltration-based, physically realistic model, that involves soil characteristics as a component of the infiltration process.

A few existing distributed models (Green-Ampt [1911], Horton [1933], Philip [1957]) can be said to meet the above requirements, while describing instantaneous infiltration rates during a design storm. The possibility of using the Green-Ampt infiltration model as an alternative infiltration approach in the SCS curve number framework was mentioned by Rallison and Miller (1981). Miller and Cronshey (1989) reported that the Soil Conservation Service (SCS) recognized the wide applicability of the Green-Ampt infiltration model and considered the future use of it as “the infiltration concept under certain conditions”.

2.3 Green-Ampt 1-D Infiltration Model

There always has been a great interest in the modeling of the infiltration process, because this process is the major factor in estimating the volume of direct runoff. W. H. Green and G. A. Ampt (1911) developed the first physically based model. This model employs a simple equation for describing and calculating infiltration. Green and Ampt arrived at their simplified theory of infiltration by considering the wetting front as a precipitous border between wetted and nonwetted soils. Figure 2.4 shows graphical representation of the Green-Ampt infiltration model: the wetting front penetrates to a depth L at time t, separating the saturated soil with hydraulic conductivity K, and moisture content η from the soil which has moisture content θ_i below the wetting front. There is ponded water with a depth of h_0 above the surface (Chow, 1998).

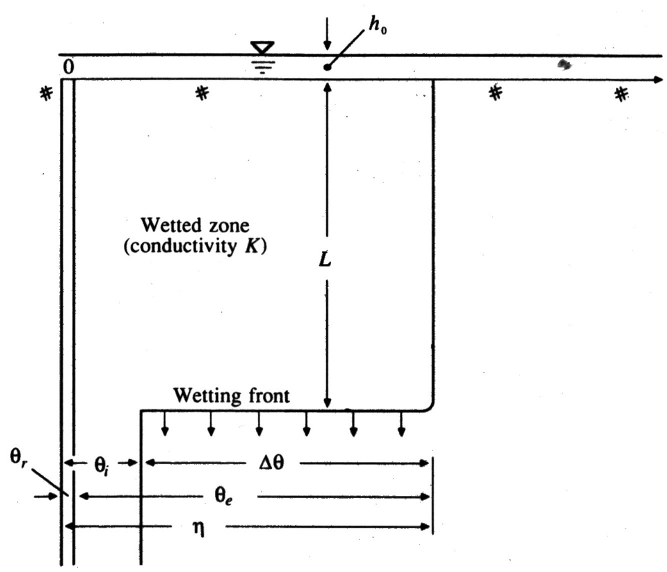

Figure 2.4 Variables in the Green-Ampt infiltration model (Chow,1988)

By applying Darcy's law to an imaginary vertical column of homogeneous soil (Figure 2.5) with a unit cross-sectional area at the top, and a control volume between soil surface and wetting front boundary, infiltration can be expressed as the total gradient which includes a capillary suction (ψ) effect due to dryness at lower levels (Bras, 1990).

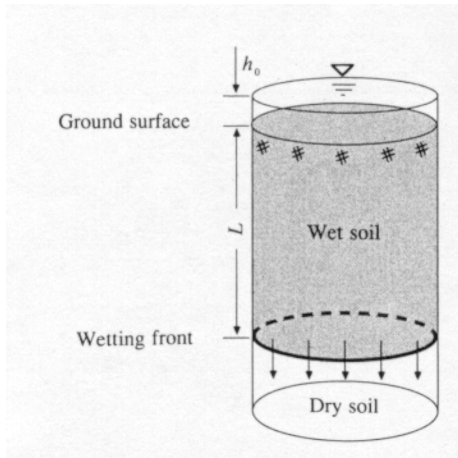

Figure 2.5 Infiltration into a column of soil of unit cross-sectional area for the Green-Ampt model (Chow, 1988).

$$f = K\frac{h_0 + \psi + L}{L} \tag{2.6}$$

For the ponded depth, h_0, considerably smaller than capillary suction and wetting front depth, equation 2.6 can be simplified as:

$$f = K\frac{\psi + L}{L} \tag{2.7}$$

From the concept of continuity, the cumulative infiltration for the column of control volume with unit cross-sectional area is $L\Delta\theta$, where $\Delta\theta$ is the change in the moisture content $(\eta-\theta_i)$. Therefore, after substituting $L = F/\Delta\theta$ into equation 2.7 we have:

$$f = \frac{dF}{dT} = K\left[\frac{\psi\Delta\theta + F}{F}\right] \quad (2.8)$$

By performing mathematical operations in order to solve equation 2.8 for *F*, the Green-Ampt equation for accumulative infiltration is obtained:

$$F(t) - \psi\Delta\theta \ln\left(1 + \frac{F(t)}{\psi\Delta\theta}\right) = Kt \quad (2.9)$$

The equation assumes that water will start ponding on the surface from the beginning of a rainfall event. In many cases, however, there is some period of time prior to ponding when potential infiltration capacity of the soil is greater than rainfall intensity. During this period all available precipitation penetrates into the soil until the soil surface becomes saturated. Thus, the infiltration process falls into two stages: infiltration before ponding and after ponding. Mein and Larson (1973) modified the Green-Ampt equation for two-stage infiltration by evaluating the time period prior to ponding (t_p) as:

$$t_p = \frac{K\psi\Delta\theta}{i(i-K)} \quad (2.10)$$

where ***i*** = constant precipitation rate.

The cumulative infiltration before ponding begins is:

$$F_p = i * t_p \quad (2.11)$$

The Green-Ampt equation for cumulative two-stage infiltration after ponding is:

$$F - F_p - \psi\Delta\theta \ln\left[\frac{\psi\Delta\theta + F}{\psi\Delta\theta + F_p}\right] = K(t - t_p) \quad (2.12)$$

The above two-stage model developed by Mein and Larson, is a more accurate representation of the actual infiltration process for rainfall events with delayed rainfall excess. Solutions for equations 2.9 and 2.12 can be obtained by the method of successive substitution or by the Newton-Raphson iteration method, which is more complicated but requires fewer iterations (Chow, 1988).

Li, Stevens, and Simons (1976) developed a quadratic approximation of the Green-Ampt equation. The explicit solution gives a maximum error of 8%, when the approximation is performed on the accumulated infiltration volume (F) first and not on the infiltration rate (f). Investigators presented the implicit solution by refining the explicit solution using the second-order Newton method. The resulting error is 0.003%.

Stone, Hawkins, and Shirley (1994) derived their approximation based on two first terms in a Taylor-series expansion. This approximation can be used for any event of constant rainfall and variable time to ponding. The investigation of approximation shows a good result (3.5%) in terms of maximum error, and a better fit to the Green-Ampt infiltration depth compared to the quadratic approximation. Salvucci and Entekhabi (1994) introduced the Explicit Green-Ampt model, whose four-term expression yields an error of less than 2% on infiltration estimation for any given time period.

2.4 Green-Ampt Parameters

The Green-Ampt infiltration equation involves three parameters which need to be estimated. Considering the sensitivity of the Green-Ampt equation, these three can be placed in order of most to least significant impact on the equation:

1. Hydraulic conductivity, K (cm/hr),
2. Wetting front capillary pressure head, ψ (cm),
3. Change in moisture content, $\Delta\theta$, which is a difference between porosity, η, and initial soil water content, θ_i.

Bouwer (1966) investigated hydraulic conductivity changes relative to the pressure head of soil water, taking into account atmospheric pressure. From the available data, hydraulic conductivity, K, in the wetted zone during infiltration is assumed to be half of saturated hydraulic conductivity.

Brooks and Corey (1964) studied variations of the suction head, ψ, with moisture content, θ. By performing laboratory tests on many different soils, they developed a graphical and, then, an empirical relationship between soil suction head and effective saturation, s_e, known as the Brooks-Corey equation:

$$s_e = \left[\frac{\psi_b}{\psi} \right]^{\lambda} \tag{2.13}$$

where ψ_b = bubbling pressure or air entry pressure,

λ = pore-size distribution index.

Two constants ψ_b and λ were defined as a result of a number of experiments on different soils. During the experiments, capillary pressure and effective saturation were recorded and plotted in logarithmic scales against each other. Analyzing the Brooks-Corey equation, slopes of the resulting curves are equal to $-1 / \lambda$ and intersections with the s_e-axis are $ln\psi_b$.

The effective saturation also can be expressed as the ratio of the available moisture, $\theta_i - \theta_r$ (for initial condition) to the maximum possible moisture content or effective porosity, θ_e:

$$s_e = \frac{\theta_i - \theta_r}{\theta_e} \tag{2.14}$$

where: θ_r = drained residual moisture content,

θ_e = effective porosity = η-θ_r

By rearranging equation 2.14 as an expression for θ_i, the change in the moisture content, $\Delta\theta$, can be expressed as:

$$\Delta\theta = \theta_e (1 - s_e) \tag{2.15}$$

Brakensiek, Engleman, and Rawls (1981) estimated and examined for normality the parameters of Green-Ampt and Brooks-Corey equations for 10 soil classes scaling from sand to clay. The investigation proved the good fit of the Brooks-Corey equation to the soil characteristics data for capillary pressure less than bubbling pressure. Mean values and standard deviation of Green-Ampt parameters were obtained for each soil class.

Rawls, Brakensiek, and Miller (1983) also used the Brooks-Corey equation to calculate Green-Ampt parameters. They analyzed approximately 1200 soils covering 34 states and employed all available soil survey information. The best result in the distinction of the Green-Ampt parameters was obtained by using soil classification according to the soil texture classes. The mean values and standard deviations of the parameters for 11 soil textures and three major horizons were summarized in a table (Table 4.1).

2.5 Green-Ampt and Curve Number Runoff Predictions

Rawls and Brakensiek (1986) made a comparison between Green-Ampt and SCS curve number runoff volume predictions. They used data from 330 runoff events producing runoff more than 0.05 inches for watersheds of an area less than 10 acres covering a range of soils from sand loam to clay. The result of the investigation shows that the Green-Ampt infiltration procedure gives better predictions for higher volumes of runoff (more than 1 inch). The rainfall excess distribution provided by the Green-Ampt procedure can be used as direct input to a hydrograph model. Work of James, Warinner, and Reedy (1992) generally proved the Rawls and Brakensiek result that the Green-Ampt model predicts direct runoff closer to realistic values.

Several researchers made attempts to relate curve numbers (CN) to Green-Ampt hydraulic conductivity values. The purpose of developing the relationship between those two is to apply the widely available information of Curve Number method to the newly developed hydrologic models, which utilize the Green-Ampt infiltration equation. Nearing, Liu, Risse, and Zhang (1996) explored the possibility of applying curve number technology to the Water Erosion Prediction Project (WEPP) model in order to predict direct runoff. The investigators determined optimum values of the effective hydraulic conductivity for which average annual runoffs for a 20-year simulation calculated by the curve number and WEPP models became equal. The optimum effective conductivities were described as a function of soil properties and land use and the resultant equations were tested on measured storm event data. Comparison of the predictions showed that both models performed almost equally well.

The WEPP direct runoff estimations were slightly better than the curve number for eight of ten data sets (Nearing et al., 1996). The empirical relationship between curve number and effective hydraulic conductivity was developed and defined as useful for K-calculation for some types of management practices. King, Arnold, and Bingner (1999) tried to evaluate curve number and Green-Ampt methods on one experimental watershed of 21.3 km^2 area by using the Soil and Water Assessment Tool (SWAT) model. Reported results of SWAT simulated annual, monthly, and daily surface runoff value and do not show any significant advantage of one model over another.

Considerable work in illustrating the advantages of the Green-Ampt infiltration model and relating the model parameters to the SCS curve numbers was done by J. A. Van Mullem. The author applied the Green-Ampt model to 12 watersheds in Montana and Wyoming of area range from 1 mi^2 to 50 mi^2 (Van Mullem, 1989). The modeled 99 rainfall events were used to predict peak discharges and runoff volumes for both the Green-Ampt and the Curve Number models. The comparison with measured values of runoff showed that using the Green-Ampt as an infiltration model within the Curve Number procedure gives better predictions of peak discharges and runoff volumes. Mean peak discharges estimated by the Green-Ampt model were closer to the measured mean, and the standard error was less for 11 of 12 watersheds. The standard error of estimating direct runoff volumes was lower for 9 of 12 watersheds compared to 6 of 12 for the Curve Number method. An additional significant advantage of the Green-Ampt method is its superior modeling of short duration and high intensity rainfall events (Van Mullem, 1991). During the investigation Van Mullem also derived a relationship between the Green-Ampt hydraulic conductivity (K) and the SCS curve number (CN) that offers the possibility of utilizing the SCS available data in various cover condition for modeling by the Green-Ampt method.

CHAPTER 3

METHODS AND DATA USED

3.1 Hydrographs

Surface runoff as a function of rainfall is affected by many factors that are often difficult to define. In order to overcome this problem and estimate the transfer function between rainfall and runoff, the unit hydrograph concept was proposed by Sherman in 1932. This concept is used to produce a hydrograph for any given rainfall event and can be applied to any midsize watershed. The unit hydrograph is defined as a hydrograph of direct runoff produced by a unit volume (usually 1 in. or 1 cm) of effective rainfall of any specified duration. The term "unit" does not denote a unit of time of storm duration. For the same watershed every specific storm duration produces a specific unit hydrograph. Unit hydrographs can be obtained from rainfall-runoff data or, for ungaged locations, by using a synthetic unit hydrograph formula.

Once a unit hydrograph for a given duration is developed, it can be used to derive the hydrograph for any runoff depth with the assumption that the time base is a constant. By assuming principles of linearity, the multiplication of the ordinates of the unit hydrograph and a particular runoff depth will produce values of ordinates of the hydrograph for such a runoff depth. The hydrograph for a storm consisting of a number of sequential runoff depths is calculated by summation of corresponding ordinates of hydrographs for different depths by lagging them by a time increment equal to the unit hydrograph duration (principle of superposition). The process of calculating direct runoff from a design storm by using the unit hydrograph is called convolution. Although the assumption of linearity is not strictly true, the results obtained by applying the unit hydrograph technique are acceptable for practical purposes.

The flood hydrograph development procedure using the SCS CN method is described in Chapter 16, Section 4 of the National Engineering Handbook (NEH-4, 1972). Derived from many natural unit hydrographs from numerous watersheds of diverse size and location, the dimensionless unit hydrograph was developed by Victor Mockus in the 1950s. Represented in Figure 3.1**,** the dimensionless unit hydrograph has

37.5 percent of total volume in the rising side. The hydrograph ordinate values are expressed as a dimensionless ratio of discharge to peak discharge (q/q_p) and abscissa values are ratios of time to time to peak (t/T_p).

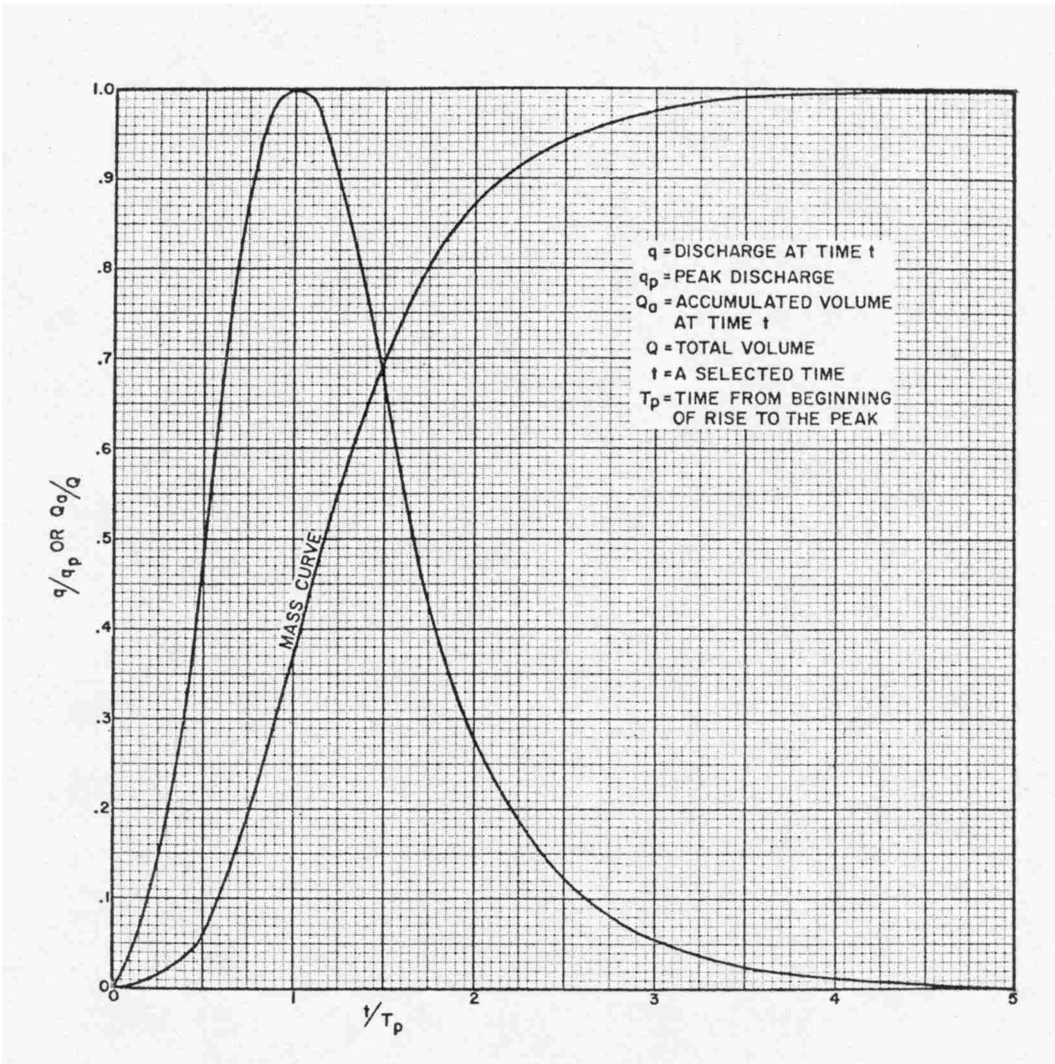

Figure 3.1 SCS dimensionless unit hydrograph and mass curve (NEH-4, 1972)

The dimensionless unit hydrograph can be represented by a triangular shape with the same percent of area in the rising side. The relationships between major hydrograph components, which are presented in Figure 3.2, were derived for the geometric features of a triangle.

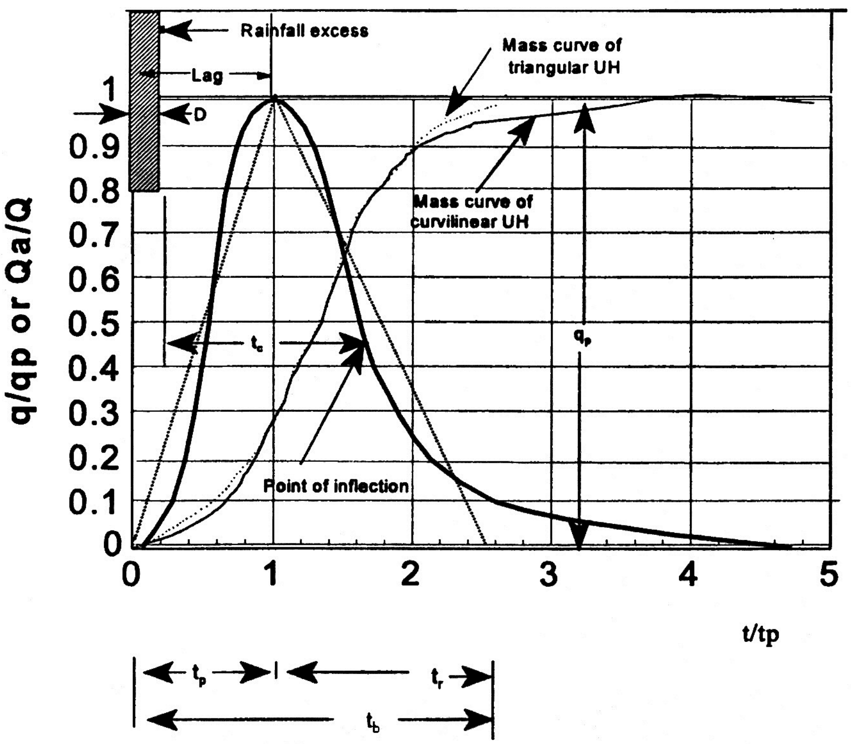

Figure 3.2 Triangular hydrograph equivalent to dimensionless curvilinear unit hydrograph (NEH-4, 1972)

The SCS CN method is based on components and their relations as follows (Ponce, 1989):

- Triangular time base to time-to-peak, $T_{bt}/t_p = 8/3$;
- Actual time base to time-to-peak, $T_b/t_p = 5$;
- Time-to-peak to unit hydrograph duration, $t_p/t_r = 5$;
- Time-to-peak to basin lag, $t_p/t_l = 10/9$;
- Unit hydrograph duration to basin lag, $t_r/t_l = 2/9$;
- Basin lag to time of concentration, $t_l/t_c=6/10$;
- Unit hydrograph duration to time of concentration, $t_r/t_c=2/15$.

The SCS CN method uses the following formula (SI units) developed by the SCS from agricultural watershed data (SCS, 1972) to calculate the basin lag:

$$t_l = \frac{L^{0.8}\left[2540 - 22.86 * CN\right]^{0.7}}{14104 * CN^{0.7} * Y^{0.5}} \tag{3.1}$$

where: t_l = catchment or basin lag (time from the centroid of effective rainfall to the peak discharge) (hr);

L = hydraulic length (m);

CN = curve number;

Y = average watershed slope (m/m).

The application of equation 3.1 is limited by watershed area (less than 16 km^2) and curve numbers in the range of 50 to 95.

The unit hydrograph peak flow equation in SI units is:

$$q_p = \frac{2.08\, AQ}{t_p} \tag{3.2}$$

where: q_p = peak discharge (m^3/s);

A = drainage area (km^2);

Q = runoff volume is equal to 1 cm of depth over the area;

2.08 = the constant, or peak rate factor that includes some shape coefficients and units conversion value;

t_p = time-to-peak (hr).

The incremental unit hydrograph for a particular watershed is obtained by convolution of the dimensionless unit hydrograph values. The runoff hydrograph is calculated by applying rainfall event distribution and corresponding accumulated runoff values to summed ordinates of the incremental unit hydrograph. The procedure of determination of coordinates for the flood hydrograph is fully shown in Example 1, Chapter 16 of the NEH-4. The SCS Computer Program for Project Formulation, Technical Release Number 20 (SCS, 1982), commonly known as TR-20, converts rainfall excess values into runoff hydrographs according the SCS procedure.

For the purposes of the present study, however, it is necessary to see the exact unit hydrograph construction and convolution in order to make a detailed comparison of the Curve Number and Green-Apmt runoff distributions. The TR-20 computer program does not provide such information. The other disadvantage to using the TR-20 is the inflexible input options that make it unable to work with the excess runoff directly and, consequently, with the Green-Ampt infiltration model. For both of these reasons a new computer program was written which allows the utilization of both the Green-Ampt and CN runoff distributions in the same run and for the same design storm characteristics.

3.2 Rainfall Distribution

In order to predict the hydrologic response of midsize catchments, it is necessary to input rainfall volume changes with time (hyetograph), or, in other words, the temporal storm distribution. For a fixed rainfall depth and duration, different storm distributions produce different responses with distinguishable peak discharges and time bases of hydrographs. Design methods in the majority of cases use synthetic design storm events that are derived from analysis of observed storms.

The SCS developed four dimensionless rainfall distributions for areas less than 1050 km^2 and durations up to and including 24 hours. The storm distributions were obtained from the Weather Bureau's Rainfall Frequency Atlases. Rainfall depths were determined for every 6-minute increment of storm event, with a duration range from 6 minutes to 24 hours. It was found from the analysis that the time to peak is location dependent. For Types I and IA, the peak intensity appears around 8 hours from the beginning of rainfall, while for Types II and III the peak happens at the middle of the storm. The highest 6-minute depth value was placed at the corresponding peak, the second highest depth was located in the next 6-minute interval, and so on, so that the smallest depth falls at the beginning and end of the 24-hour rainfall event (McCuen, 1989). The resulting distributions are presented in Figure 3.3 and Table 3.1.

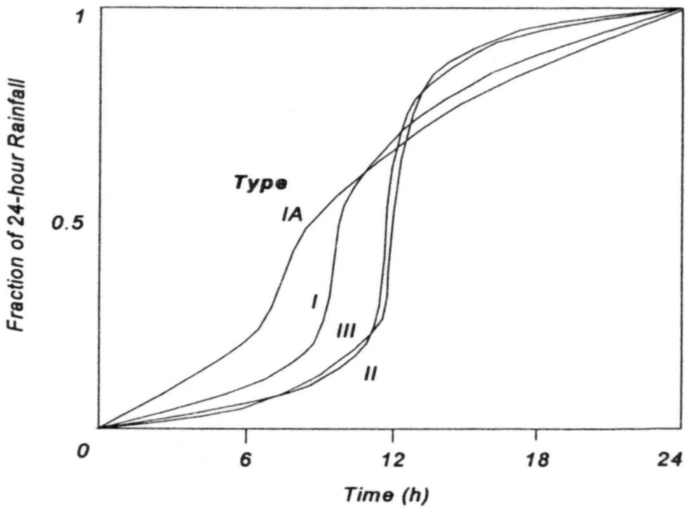

Figure 3.3 SCS 24-hr rainfall distributions (not to scale)
(McCuen et al., 1996)

Type I is applicable to the Pacific maritime climate with dry summers and wet winters. For the Pacific Northwest and Northern California with frontal low-intensity precipitation, Type IA distribution should be used. Type III represents large, 24-hour long tropical storms typical of the Gulf and Atlantic coastal areas. Type II applies to the rest of the U.S. and corresponds to highly intensive rainfalls. Figure 3.4 shows the locations of the regions and corresponding types of distributions. The type II storm distribution, which is recommended for most of the United States, including WV, was selected as the design storm distribution for the presented work.

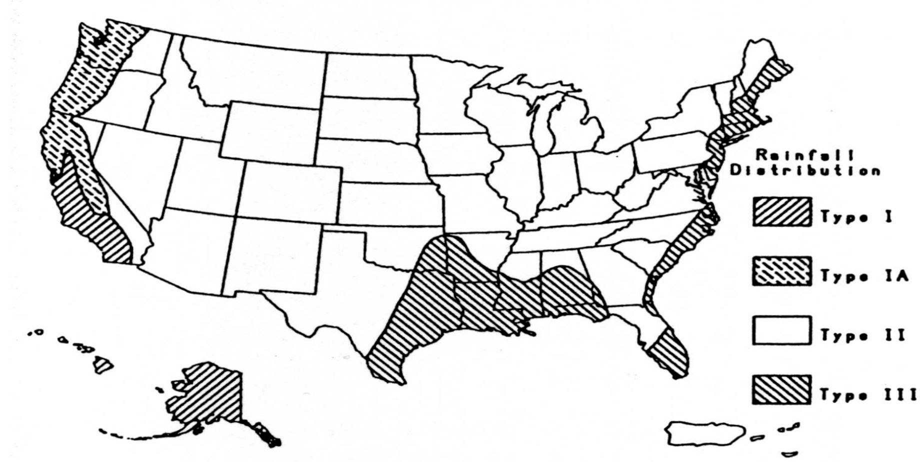

Figure 3.4 Approximate geographic areas for SCS rainfall distributions

Table 3.1 SCS Cumulative, Dimensionless One-day Storms (McCuen, 1996)

Time (h)	Type I Storm	Type IA Storm	Type II Storm
0	0	0	0
0.5	0.008	0.010	0.0053
1.0	0.017	0.020	0.0108
1.5	0.026	0.035	0.0164
2.0	0.035	0.050	0.0223
2.5	0.045	0.067	0.0284
3.0	0.055	0.082	0.0347
3.5	0.065	0.098	0.0414
4.0	0.076	0.116	0.0483
4.5	0.087	0.135	0.0555
5.0	0.099	0.156	0.0632
5.5	0.112	0.180	0.0712
6.0	0.126	0.206	0.0797
6.5	0.140	0.237	0.0887
7.0	0.156	0.268	0.0984
7.5	0.174	0.310	0.1089
8.0	0.194	0.425	0.1203
8.5	0.219	0.480	0.1328
9.0	0.254	0.520	0.1467
9.5	0.303	0.550	0.1625
10.0	0.515	0.577	0.1808
10.5	0.583	0.601	0.2042
11.0	0.624	0.624	0.2351
11.5	0.655	0.645	0.2833
12.0	0.682	0.664	0.6632
12.5	0.706	0.683	0.7351
13.0	0.728	0.701	0.7724
13.5	0.748	0.719	0.7989
14.0	0.766	0.736	0.8197
14.5	0.783	0.753	0.8380
15.0	0.799	0.769	0.8538
15.5	0.815	0.785	0.8676
16.0	0.830	0.800	0.8801
16.5	0.844	0.815	0.8914
17.0	0.857	0.830	0.9019
17.5	0.870	0.844	0.9115
18.0	0.882	0.858	0.9206
18.5	0.893	0.871	0.9291
19.0	0.905	0.844	0.9371
19.5	0.916	0.896	0.9446
20.0	0.926	0.908	0.9519
20.5	0.936	0.920	0.9588
21.0	0.946	0.932	0.9653
21.5	0.956	0.944	0.9717
22.0	0.965	0.956	0.9777
22.5	0.974	0.967	0.9836
23.0	0.983	0.978	0.9892
23.5	0.992	0.989	0.9947
24.0	1.000	1.000	1.0000

3.3 Design Storms

The precipitation depth range was selected according to data from rainfall frequency atlases, which are published in the TR-55 manual (SCS, 1986). Over the area, where Type II rainfall distribution is applied the lowest depth for 2-year 24-hour rainfall is approximately 4 cm (1.5 in) and the largest depth for 100-year 24-hour storm is approximately 36 cm (14 in). The graphical relationship between the Green-Ampt hydraulic conductivity and the SCS curve numbers was obtained for the above selected storm depth range, using intervals of 4 cm. However, for runoff hydrograph computation this range was narrowed to 8 cm to 32 cm with intervals of 8 cm to avoid an excessive number of examples. Such a diminution was made due to the intention of the project to analyze the most typical conditions.

3.4 Watershed Characteristics

Considering the limitations of the SCS Curve Number method regarding catchment size, and in order to simplify calculation of area and slope, a small hypothetical watershed was used for the present investigation. The watershed is of square shape in plan projection, with a length on each side of 1000 meters, and an area of 1 km^2. The watershed area was selected to be representative of a typical SCS TR-20 model subwatershed. An idealized watershed shape was judged suitable for a performance comparison between infiltration models, while simplifying those measures derived from watershed geometry. The present study does not include stream channel flow routing and, hence, any time delay and storage effects are assumed to be included in the SCS non-dimensional unit hydrograph shape. Figure 3.5 is a DEM model of the watershed, which demonstrates the shape, slope configuration, and drainage paths.

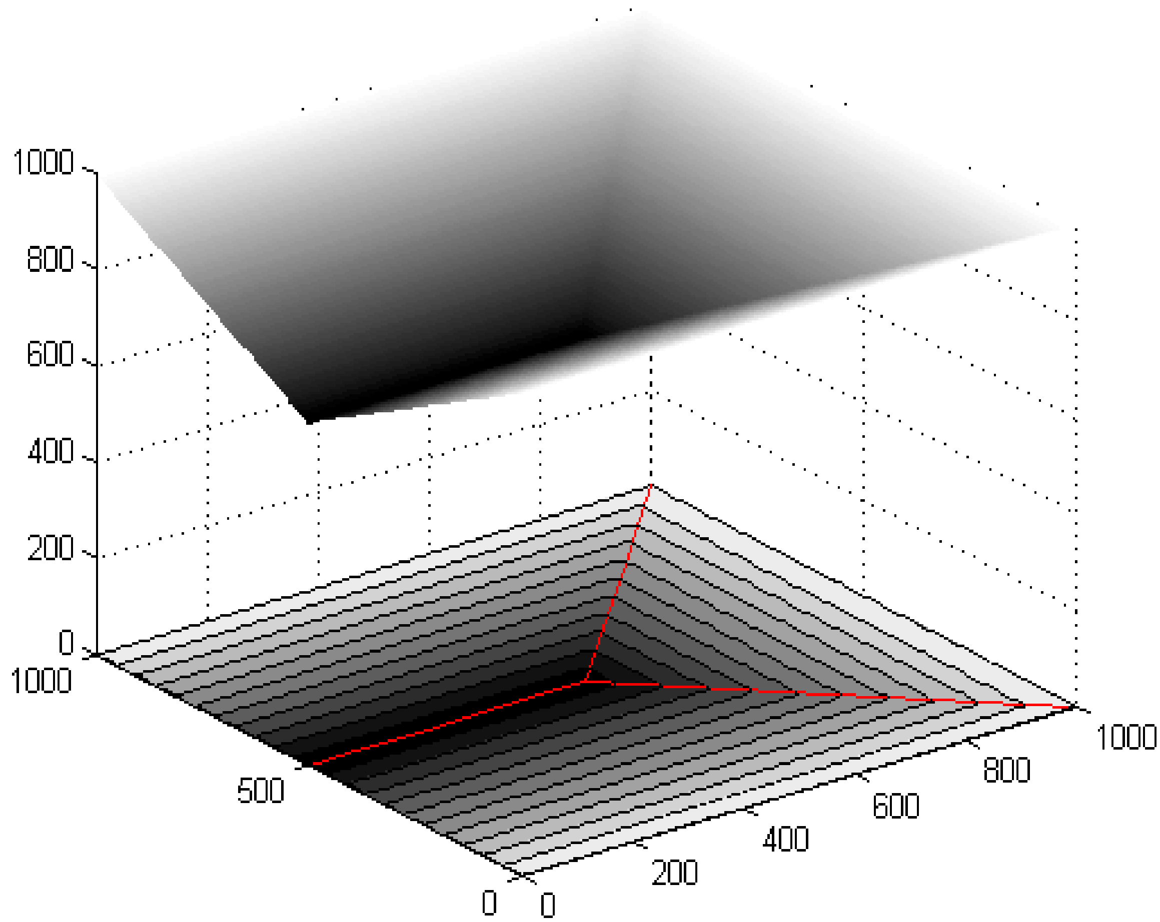

Figure 3.5 DEM and plan projection of representative watershed

CHAPTER 4

PROCEDURE

4.1 Defining the Green-Ampt Parameters

As was mentioned earlier, three Green-Ampt parameters need to be estimated in order to calculate infiltration rate and, finally, obtain the direct runoff volume by using CN procedure: hydraulic conductivity, K, wetting front capillary pressure head, ψ, and change in moisture content, $\Delta\theta$. For the purposes of the present study, average values of the Green-Ampt hydraulic conductivity and wetting front suction head determined by Rawls et al. (1983) for different soil classes were used (Table 4.1). Several studies (Brakensiek et al. [1981], Van Mullem [1989]) of the Green-Ampt parameters show that the wetted front capillary pressure is highly correlated with the hydraulic conductivity over all classes of soil texture presented in the table. In order to reduce the numbers of parameters, the relationship between mean values of ψ and K presented in Table 4.1 for 11 USDA soil texture classes was investigated by performing a linear regression analysis of logarithms of ψ, versus K. Figure 4.1 represents a linear regression fit to the plotted data points with one standard deviation for the wetting front capillary pressure, ψ, in each (positive or negative) direction. The resulting relationship equation is:

$$\log\psi = -0.3266 * \log K + 1.0177 \tag{4.1}$$

Table 4.1 Green and Ampt Parameters According to Soil Texture Classes and Horizons (Rawls et al., 1983)

Soil texture Class (1)	Horizon (2)	Sample Size (3)	Total porosity, φ, cm^3/cm^3 (4)	Effective porosity, θ_e, cm^3/cm^3 (5)	Wetted front capillary pressure, ψ_f,[a] cm (6)	Hydraulic conductivity, K,[b] cm/hr (7)
Sand [c]		762	0.437 (0.374-0.500)[d]	0.417 (0.354-0.480)	4.95 (0.97-25.36)	11.78
	A	370	0.452 (0.396-0.508)	0.431 (0.375-0.487)	5.34 (1.24-23.06)	
	B	185	0.440 (0.385-0.495)	0.421 (0.365-0.477)	6.38 (1.31-31.06)	
	C	127	0.424 (0.385-0.463)	0.408 (0.365-0.451)	2.07 (0.32-13.26)	
Loamy Sand		338	0.437 (0.363-0.506)	0.401 (0.329-0.473)	6.13 (1.35-27.94)	2.99
	A	110	0.457 (0.385-0.529)	0.424 (0.347-0.501)	6.01 (1.58-22.87)	
	B	49	0.447 (0.379-0.515)	0.412 (0.334-0.490)	4.21 (1.03-17.24)	
	C	36	0.424 (0.372-0.476)	0.385 (0.323-0.447)	5.16 (0.76-34.85)	
Sandy Loam		666	0.435 (0.351-0.555)	0.412 (0.283-0.541)	11.01 (2.67-45.47)	1.09
	A	119	0.505 (0.399-0.611)	0.469 (0.330-0.608)	15.24 (5.56-41.76)	
	B	219	0.466 (0.352-0.580)	0.428 (0.271-0.585)	8.89 (2.02-39.06)	
	C	66	0.418 (0.352-0.484)	0.389 (0.310-0.468)	6.79 (1.16-39.65)	
Loam		383	0.463 (0.375-0.551)	0.434 (0.334-0.534)	8.89 (1.33-59.38)	1.09
	A	76	0.512 (0.427-0.597)	0.476 (0.376-0.576)	10.01 (2.14-46.81)	
	B	67	0.512 (0.408-0.616)	0.498 (0.382-0.614)	6.40 (1.01-40.49)	
	C	47	0.412 (0.350-0.474)	0.382 (0.305-0.459)	9.27 (0.87-99.29)	
Silt Loam		1206	0.501 (0.420-0.582)	0.486 (0.394-0.578)	16.68 (2.92-95.39)	0.34
	A	361	0.527 (0.444-0.610)	0.514 (0.425-0.603)	10.91 (1.89-63.05)	
	B	267	0.533 (0.430-0.636)	0.515 (0.387-0.643)	7.21 (0.86-60.82)	
	C	73	0.470 (0.409-0.531)	0.460 (0.396-0.524)	12.62 (3.94-40.45)	
Sandy Clay Loam		498	0.398 (0.332-0.464)	0.330 (0.235-0.425)	21.85 (4.42-108.0)	0.65
	A	---[e]	----- --------- --------	---- --------- ---------	----- ------ ----------	
	B	198	0.393 (0.310-0.476)	0.330 (0.223-0.437)	26.10 (4.79-142.3)	
	C	32	0.407 (0.359-0.455)	0.332 (0.251-0.413)	23.90(5.51-103.75)	
Clay Loam		366	0.464 (0.409-0.519)	0.309 (0.279-0.501)	20.88 (4.79-91.10)	0.15
	A	28	0.497 (0.434-0.560)	0.430 (0.328-0.532)	27.00 (6.13-118.9)	
	B	99	0.451 (0.401-0.501)	0.397 (0.228-0.530)	18.52 (4.36-78.73)	
	C	55	0.452 (0.412-0.492)	0.400 (0.320-0.480)	15.21 (3.79-61.01)	
Silty Clay Loam		689	0.471 (0.418-0.524)	0.432 (0.397-0.517)	27.30 (5.67-131.5)	0.10
	A	65	0.509 (0.449-0.569)	0.477 (0.410-0.544)	13.97 (4.20-46.53)	
	B	191	0.469 (0.423-0.515)	0.441 (0.374-0.508)	18.56 (4.08-84.44)	
	C	39	0.475 (0.436-0.514)	0.451 (0.386-0.516)	21.54 (4.56-101.7)	
Sandy Clay		45	0.430 (0.370-0.490)	0.321 (0.207-0.435)	23.90 (4.08-140.2)	0.06
	A	----	------ --------- --------	------- -------- -------	------- ------- -------	
	B	23	0.435 (0.371-0.499)	0.335 (0.220-0.450)	36.74 (8.33-162.1)	
	C	----	------- -------- --------	------- --------- -------	------- -------- ------	
Silty Clay		127	0.479 (0.425-0.533)	0.423 (0.334-0.512)	29.22 (6.13-139.4)	0.05
	A	----	------- -------- --------	------- --------- -------	------- --------- -----	
	B	38	0.476 (0.445-0.507)	0.424 (0.345-0.503)	30.66 (7.15-131.5)	
	C	21	0.464 (0.430-0.498)	0.416 (0.346-0.486)	45.65(18.27-114.1)	
Clay		291	0.475 (0.427-0.523)	0.385 (0.269-0.501)	31.63 (6.39-156.5)	0.03
	A	----	------- -------- --------	-------- --------- ------	------- ------- -------	
	B	70	0.470 (0.426-0.514)	0.412 (0.309-0.515)	27.72 (6.21-123.7)	
	C	23	0.483 (0.441-0.525)	0.419 (0.294-0.544)	54.65(10.59-282.0)	

[a] Antilog of the log mean and standard deviation.
[b] Values for Rawls, et al.
[c] Values for the texture class.
[d] Numbers in ( )$\pm$ one standard deviation.
[e] Insufficient sample to determine parameters.

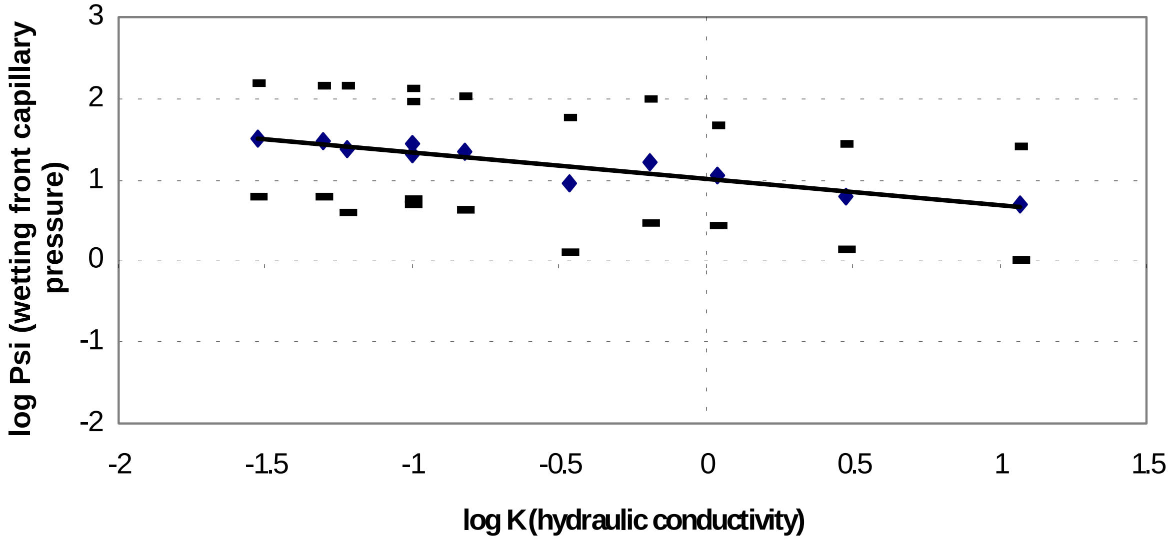

Figure 4.1 Linear regression of log (K) - log (ψ) relationship

The regression statistics for this linear relationship are shown in the following table:

Table 4.2 Regression Statistics for ψ-K Relationship

Multiple R	0.4079
R Square	0.8851
Adjusted R Square	0.8723
Standard Error	0.1008
Standard Error of coefficients	0.0381

Equation 4.1 estimates average values of ψ for corresponding K for each soil class from the Table 4.1. The equation can be applied for an estimation of parameters when limited data on soil properties are available. The investigation performed by James et al. (1992)

implies that the use of some approximations and high correlation between calculated and observed values can give good results.

The change in moisture content in the Rawls, Brakensiek, and Miller (1983) development model is defined as a difference between porosity and initial moisture content. Values for porosity were taken from Table 4.1 for mean values of hydraulic conductivity for every soil texture class. According to Rawls, Brakensiek, and Miller (1983), the values in the table were calculated based on an average initial moisture level at 1/3 bar and 15 bar soil moisture retention levels. These two values are representitive of the field capacity and the wilting point, respectively. The observations made by Rawls and Brakensiek (1986) suggest the use of soil moisture held at 1/3 bar for an average antecedent moisture condition (AMC II) as it is defined in SCS CN method. The decision for selecting the appropriate soil moisture retention level as a representation of the average moisture level condition can be made based on local soil moisture data if available (Van Mullem, 1991). The present investigation assumes the initial soil moisture content to be equal to water held at 1/3 bar as it was estimated from soil properties in the study by Rawls and Brakensiek (1982). In order to calculate the initial soil moisture level, θ_i, or, in other words, volumetric water content, the Brooks-Corey equation can be rearranged with respect to θ_i, as follows:

$$\theta_i = \theta_r + \frac{(\eta - \theta_r)\psi_b^{\lambda}}{\psi^{\lambda}} \tag{4.2}$$

The values of Brooks-Corey parameters, λ and ψ_b, in the equation are given in Table 4.3 for different soil texture classes.

Table 4.3 Brooks and Corey Parameters Estimated from Soil-Moisture Capillary Pressure*

Texture	Sq. Rt. of Pore-Size Distribution Index, $\lambda^{1/2}$ (-)	Logarithm of Bubbling Pressure $\ln\psi_b$, cm
1	**2**	**3**
Sand	0.739 (0.170)	2.853 (1.174)
Loamy Sand	0.670 (0.110)	2.273 (0.981)
Sandy Loam	0.615 (0.143)	2.820 (1.042)
Loam	0.496 (0.109)	3.144 (1.233)
Silt Loam	0.455 (0.094)	3.769 (0.966)
Sand Clay Loam	0.587 (0.155)	3.253 (1.064)
Clay Loam	0.509 (0.154)	3.305 (0.924)
Silty Clay Loam	0.405 (0.118)	3.607 (0.939)
Silty Loam	0.431 (0.162)	3.302 (0.919)
Clay	0.432 (0.166)	3.494 (1.136)

* Data is taken from Brakensiek (1981)
** Number in parenthesis is a standard deviation

The capillary pressure, ψ, of 1/3 bar corresponds to 340 cm. The residual soil water content, θ_r, was calculated as a difference between the total porosity, η, and effective porosity, θ_e, with values being taken from Table 4.1. The results of calculations of the initial moisture content by the Brooks-Corey equation are shown in Table 4.4. The change in the moisture content for 10 soil texture classes is also available in Table 4.4. The Brook-Corey parameter data for the Sandy Clay were not located in the literature.

Table 4.4 Brooks and Corey Parameters for Calculating Initial Water Content of Different Soil Texture Classes

Texture	Residual soil water content, θr, cm^3/cm^3	Total porosity, η, cm^3/cm^3	Pore size distribution index, λ	Bubbling pressure, ψ_b, cm	Initial soil water content for ψ=340 cm, θi, cm^3/cm^3	Change in moisture content, $\Delta\theta$ cm^3/cm^3
1	**2**	**3**	**4**	**5**	**6**	**7**
Sand	0.02	0.437	0.546	17.340	0.102	0.335
Loamy Sand	0.036	0.437	0.449	9.708	0.117	0.320
Sandy Loam	0.041	0.453	0.378	16.777	0.173	0.280
Loam	0.029	0.463	0.246	23.196	0.253	0.210
Silt Loam	0.015	0.501	0.207	43.337	0.332	0.169
Sandy Clay Loam	0.068	0.398	0.345	25.868	0.204	0.194
Clay Loam	0.155	0.464	0.259	27.249	0.316	0.148
Silty Clay Loam	0.039	0.471	0.164	36.855	0.339	0.132
Sandy Clay	0.109	0.430	-------	-------	-------	-------
Silty Clay	0.056	0.479	0.186	27.167	0.320	0.159
Clay	0.09	0.475	0.187	32.917	0.339	0.136

Consequently, having all the Green-Ampt parameters defined, the infiltration distribution for a 24-hour rainfall of any depth can be estimated. The "GreenADlg.cpp" computer program written in C++ language and listed in Appendix C performs the 24-hr infiltration calculations as a part of the overall program.

4.2 Relating Green-Ampt Hydraulic Conductivity to Curve Numbers

The accumulated infiltration in the SCS Curve Number method for a single rainfall depth depends only on the curve number, while in the Green-Ampt infiltration model the amount of infiltration is a function of three parameters: hydraulic conductivity, K, wetting front capillary pressure, ψ, and change in moisture content, $\Delta\theta$.

Values of the change in moisture content, $\Delta\theta$, for every soil texture are listed in Table 4.4 and the wetted front capillary pressure, ψ, is defined in Table 4.1. Hydraulic conductivity, K, was determined by the derived logarithmic relationship between K and ψ (equation 4.1) for the one standard deviation range of ψ. For each soil class the range of ψ was divided into 28 equal intervals to provide sufficient data points (29) for plotting curves of CN versus K. The Green-Ampt 24-hour infiltration values for each storm depth in range from 4 cm to 36 cm in 4-cm increments were calculated by equations 2.11 and 2.12 for each of 10 soil texture classes. The direct runoff was determined from total 24-hour precipitation and infiltration, and used to obtain an equivalent curve number by solving equations 2.3 and 2.4 for CN. The "greenampt.cpp" computer program (Appendix C) does all calculations. The resulting graphical relationships are shown in Figures 4.2-11.

For each of the storm rainfall depths (Figures 4.2-11), the Green-Ampt K value is increased continually. The infiltration capacity of the soil will increase along with the increase in K and will reach the point where 100 percent of the storm rainfall depth is infiltrated. This point in the SCS CN model corresponds to the condition of $P = 0.2S = I_a$ and the lowest (for each rainfall depth) curve number, CN, value on the plots. The SCS equation defining the relationship between S and CN is:

$$S = \frac{1000R}{CN} - 10R \qquad (4.3)$$

where R = 2.54 (units conversion coefficient to transfer inches into centimeters)

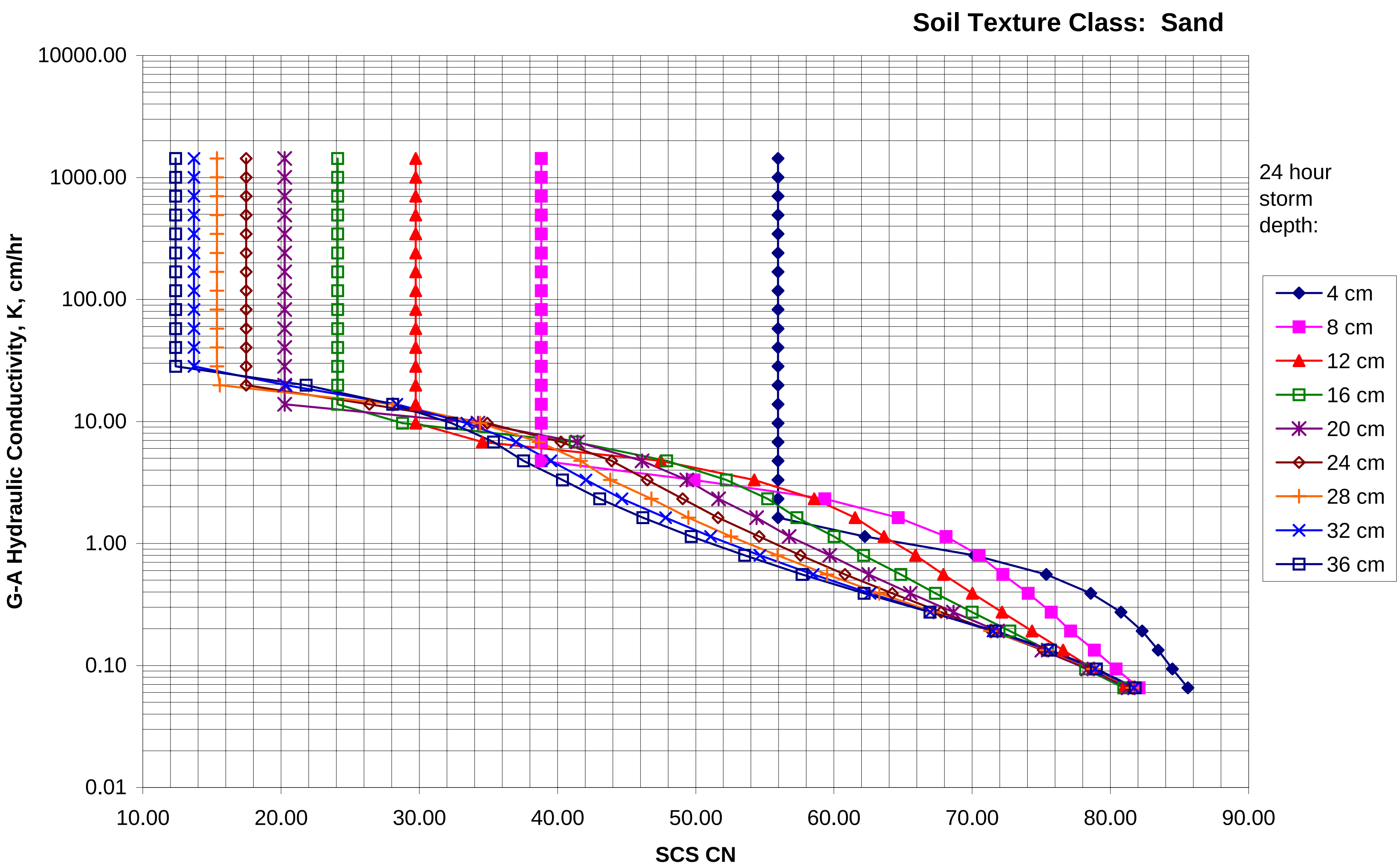

Figure 4.2 Green-Ampt K versus SCS CN for Sand, for SCS Type II 24 hr. Storm Depths

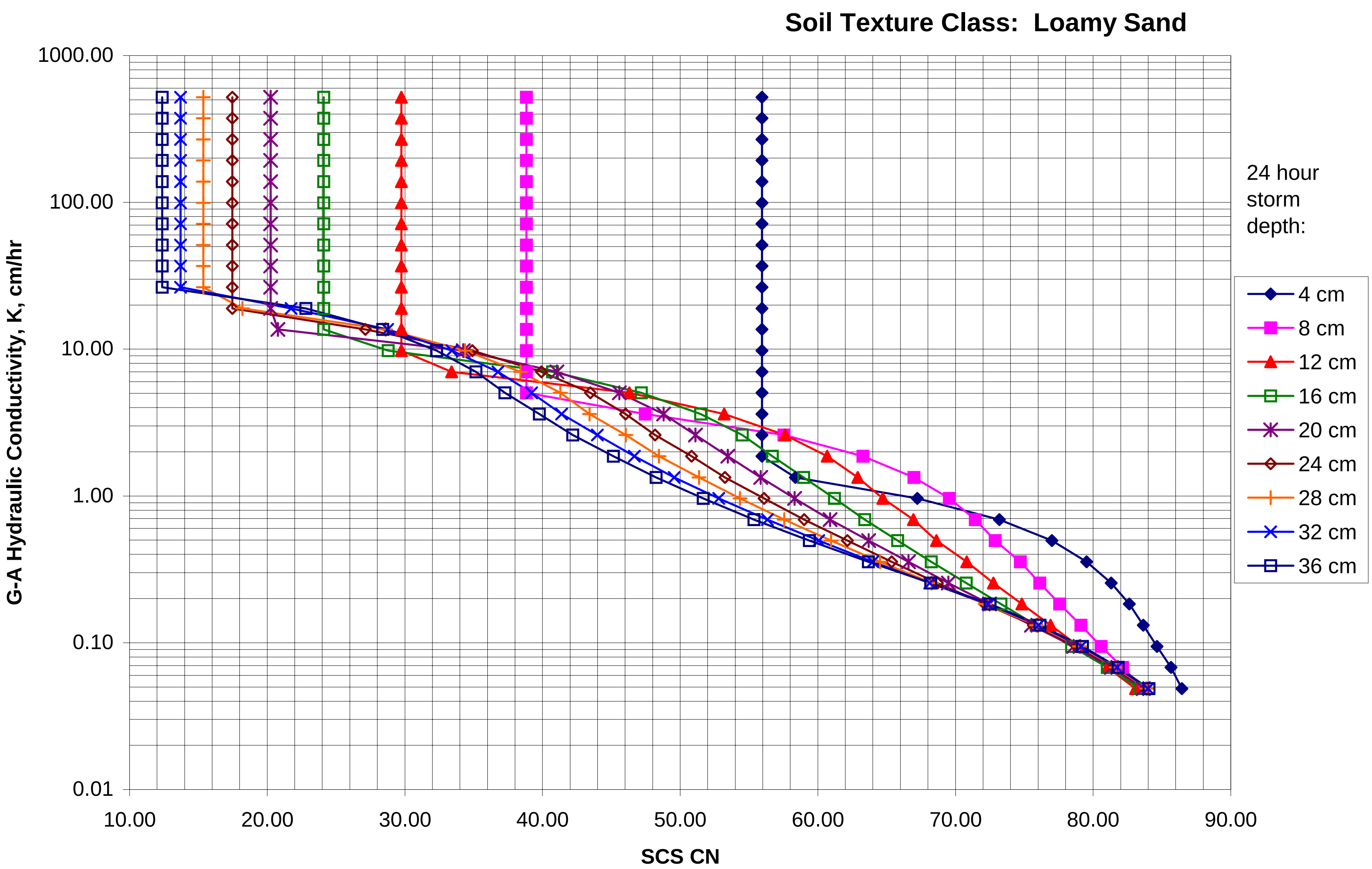

Figure 4.3 Green-Ampt K versus SCS CN for Loamy Sand, for SCS Type II 24 hr. Storm Depths

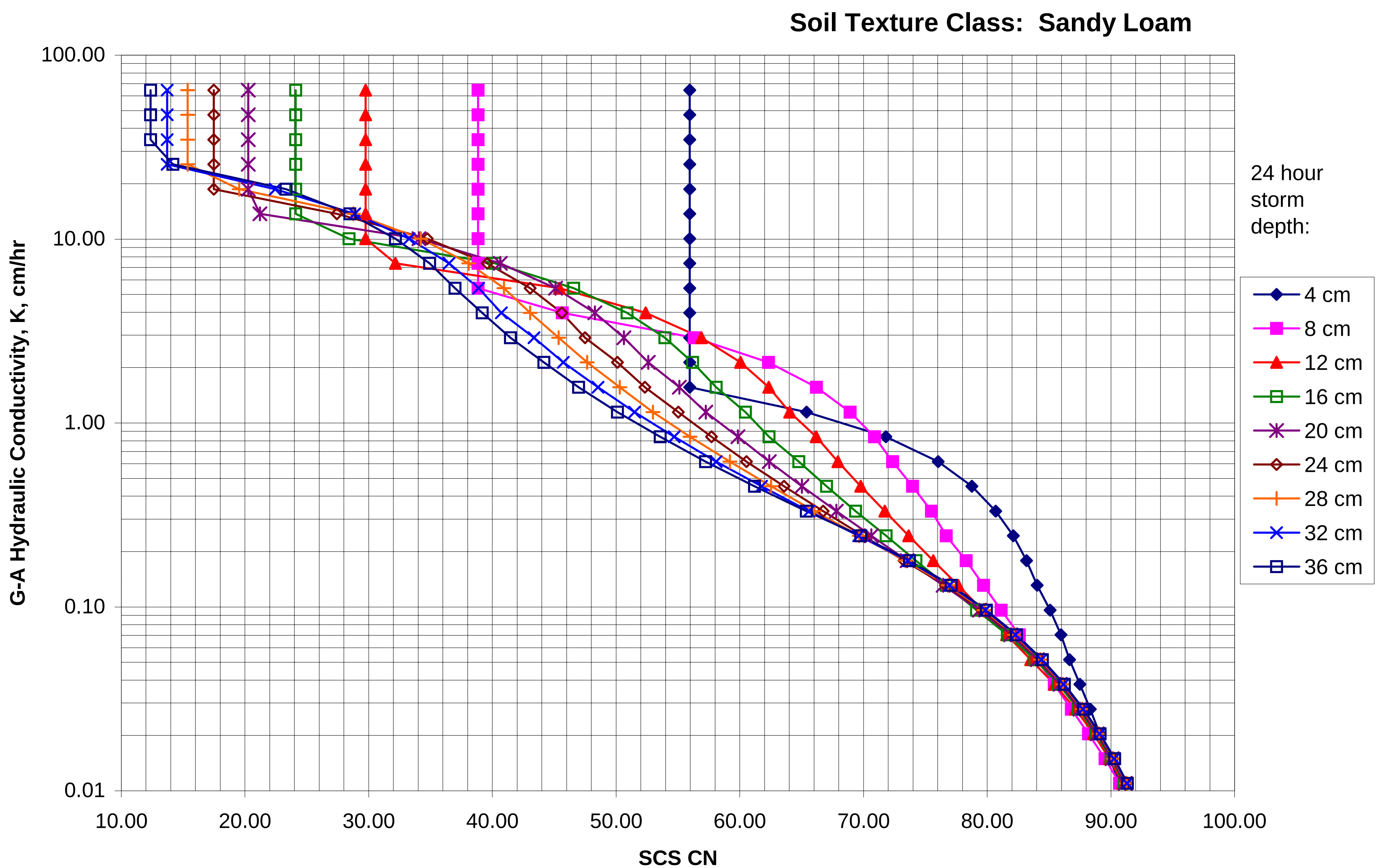

Figure 4.4 Green-Ampt K versus SCS CN for Sandy Loam, for SCS Type II 24 hr. Storm Depths

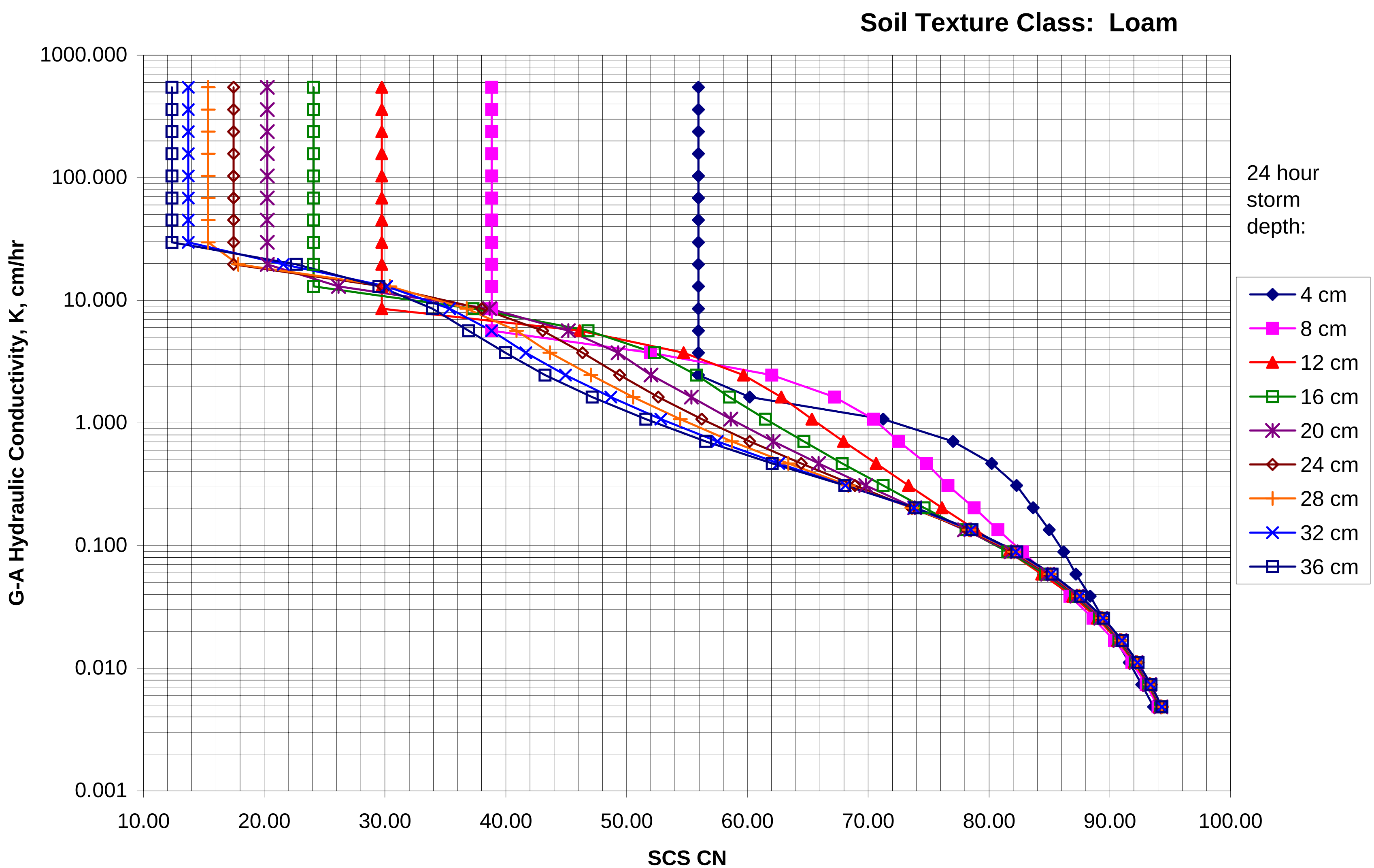

Figure 4.5 Green-Ampt K versus SCS CN for Loam, for SCS Type II 24 hr. Storm Depths

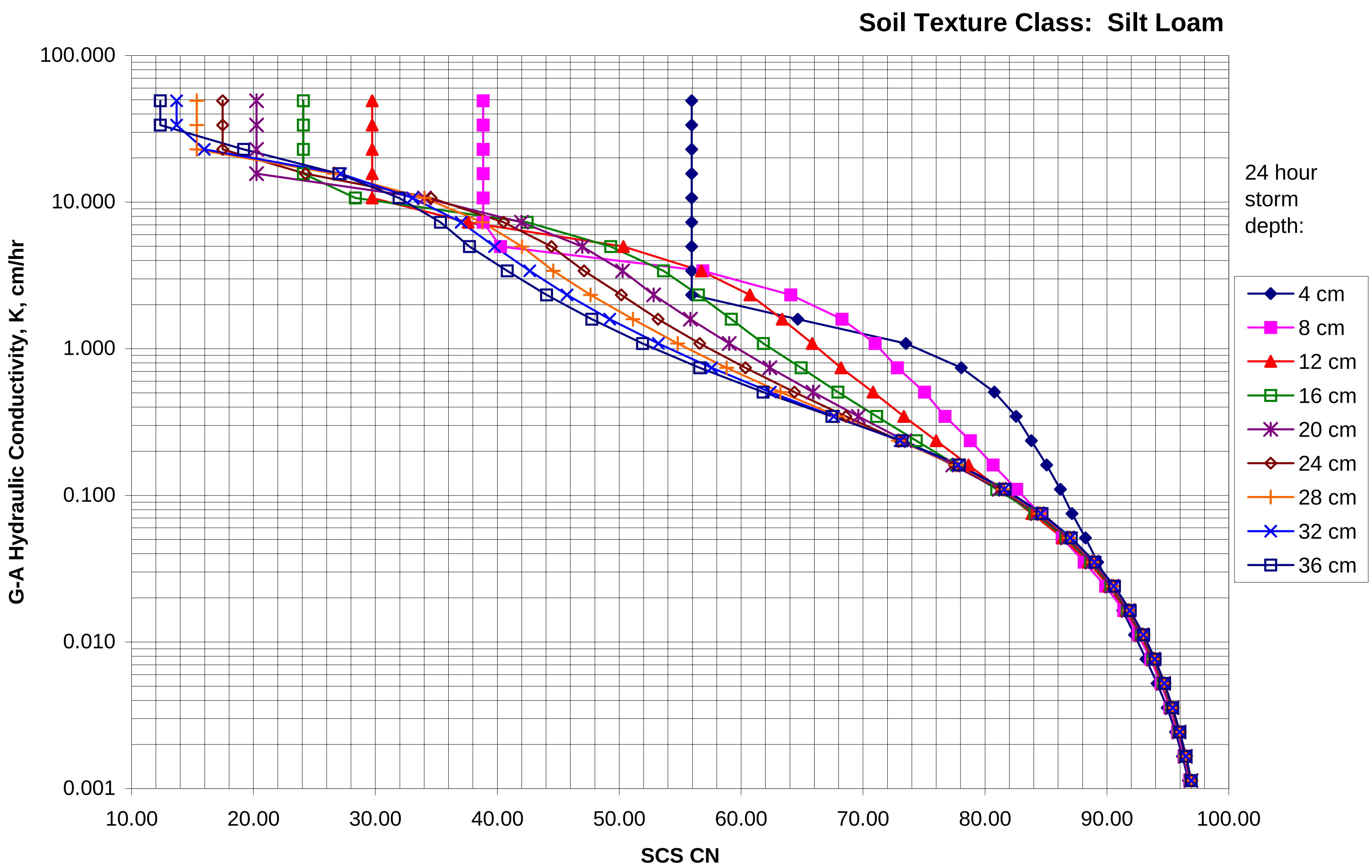

Figure 4.6 Green-Ampt K versus SCS CN for Silt Loam, for SCS Type II 24 hr. Storm Depths

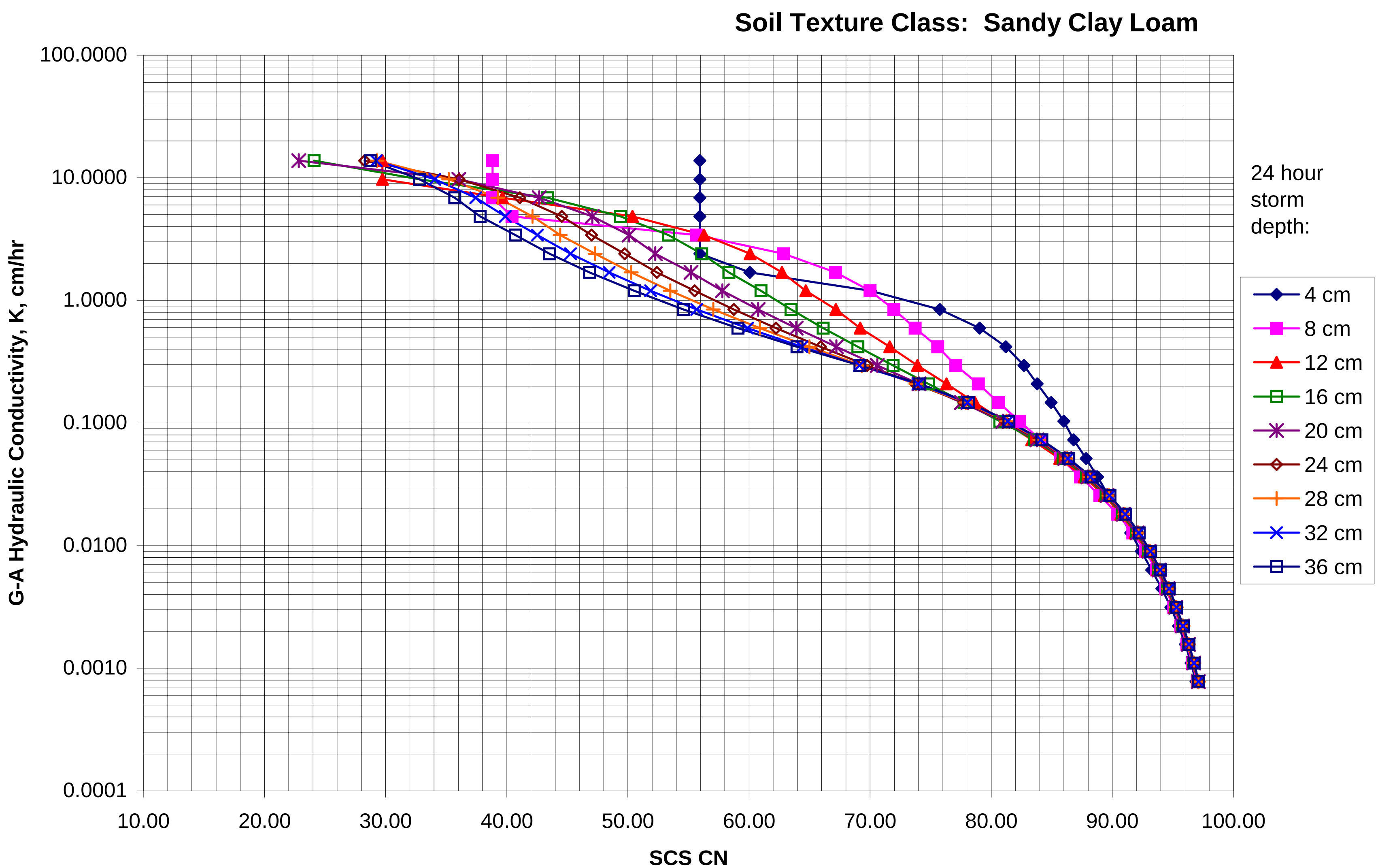

Figure 4.7 Green-Ampt K versus SCS CN for Sandy Clay Loam, for SCS Type II 24 hr. Storm Depths

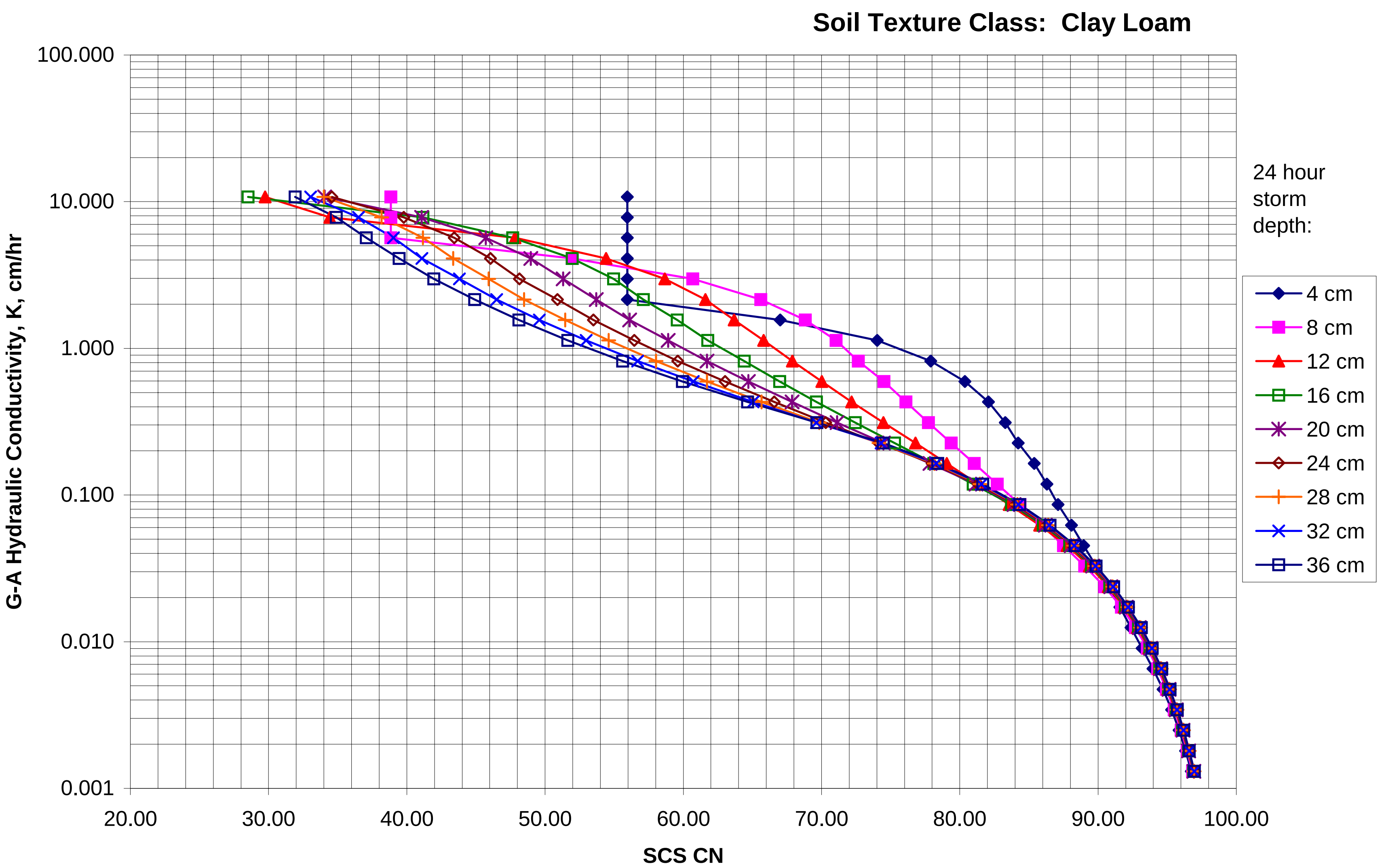

Figure 4.8 Green-Ampt K versus SCS CN for Clay Loam, for SCS Type II 24 hr. Storm Depths

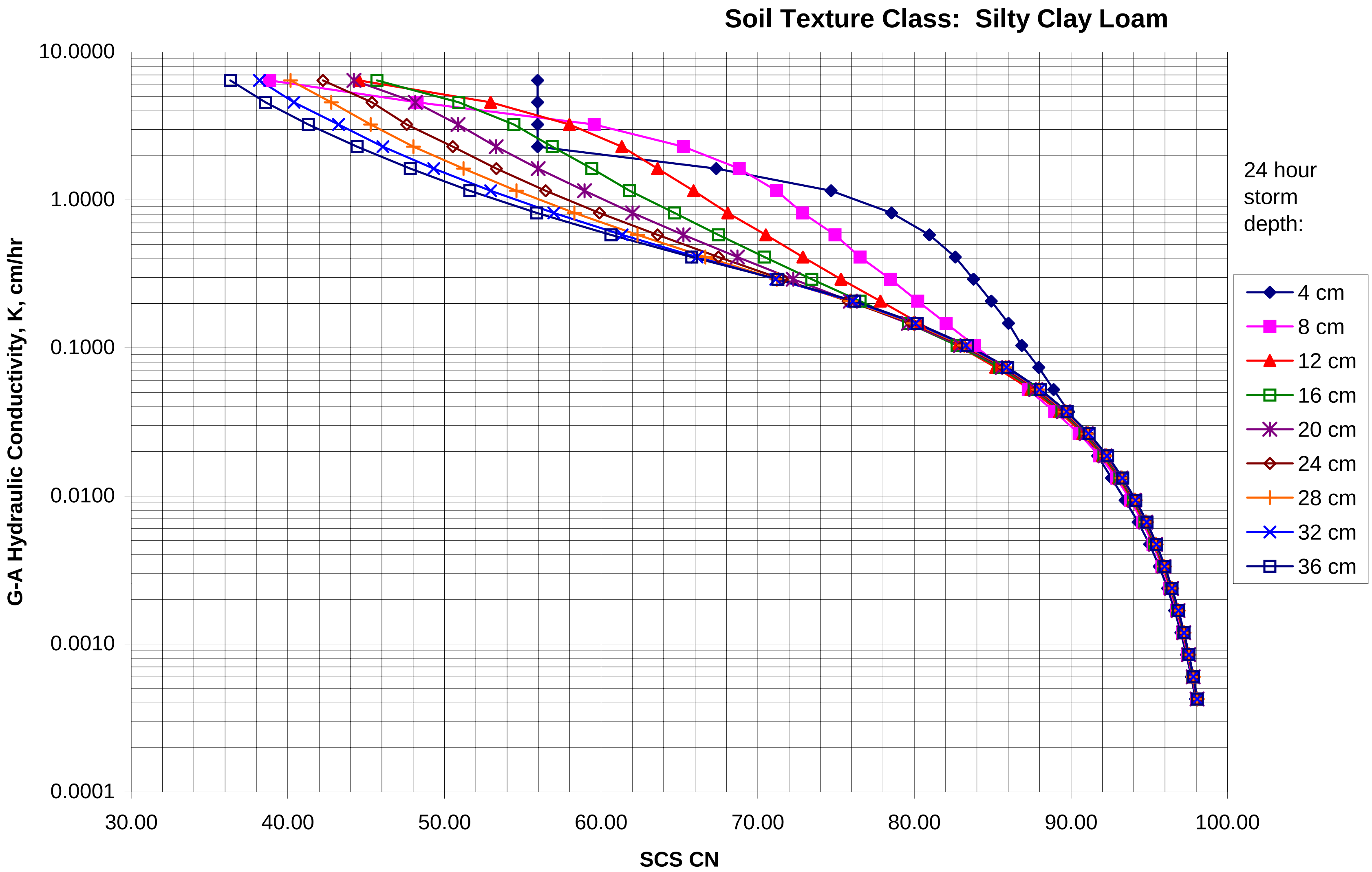

Figure 4.9 Green-Ampt K versus SCS CN for Silty Clay Loam, for SCS Type II 24 hr. Storm Depths

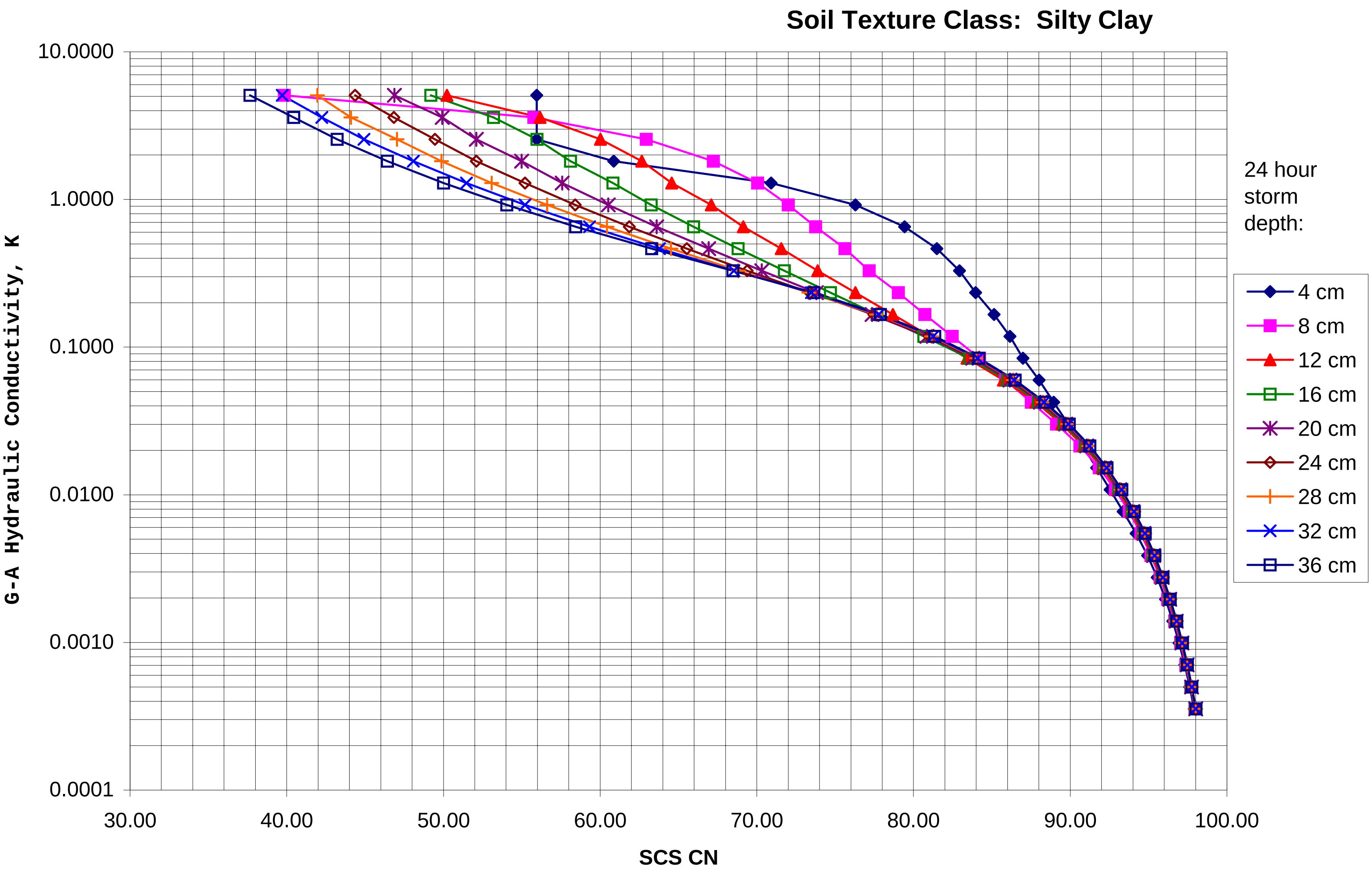

Figure 4.10 Green-Ampt K versus SCS CN for Silty Clay, for SCS Type II 24 hr. Storm Depths

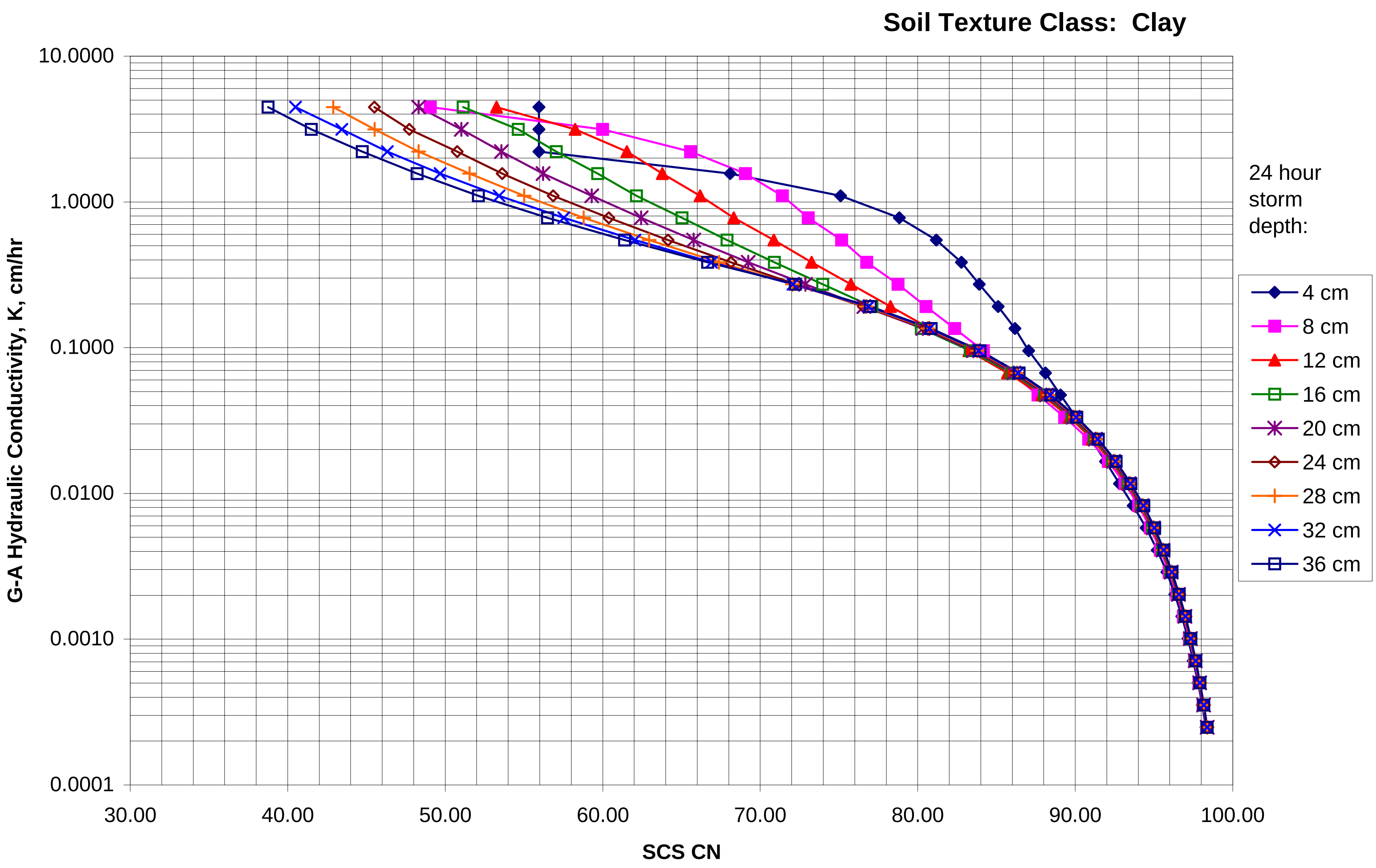

Figure 4.11 Green-Ampt K versus SCS CN for Clay, for SCS Type II 24 hr. Storm Depths

As *CN* is progressively reduced it will continually increase *S* and, eventually, a point will be reached where *CN* drops to a value low enough to increase *S* to a point where $0.2S = P$.

With future increase of *K* beyond the point where all precipitation is infiltrated, the soil simply continues to infiltrate all of the storm depth. Because the total infiltration depth, *F*, cannot exceed the storm depth, *P*, the same *CN* value is computed regardless of how much higher *K* goes beyond the first point where all the storm depth is absorbed. Therefore, the vertical line on the plots results, with *K* continuing to increase while *CN* stays constant.

Regarding Figures 4.2-11, it should be noted that, in some cases, two different rainfall depth curves of *K* versus *CN* intersect. The relationship between pairs of Curve Numbers, each corresponding to an equal value of *K*, but for different rainfall depths (*P*), is not the same before and after intersection. For example, for Sand soil and K=0.5 cm/hr, *CN*(*P*=4) is larger than *CN*(*P*=8). At the same time, after intersection for K=1 cm/hr, *CN*(*P*=4) is smaller the *CN*(*P*=8). The explanation for this requires additional calculations and observations of *CN*-*K* curves, for example for different types of rainfall distribution. This is beyond the scope of the present study, and should be the subject of a future project.

4.3 Representative Soils

Due to the number of existing soil textures (11 classes) and the curve number variations within a single hydrologic soil group (A, B, C, or D), a tremendous amount of data could potentially be produced as a result of this study. It was decided for purposes of an initial investigation to limit the number of combinations of variables. The selection of representative soils was made based on data available in the SCS Soil Survey of Marion and Monongalia Counties in West Virginia, and the hydrologic soil group description given in the TR-55 manual (SCS, 1986). The runoff hydrographs in the present study were obtained for the following hydrologic soil groups with infiltration rate limits, representative curve numbers, and soil texture classes:

- A (f > 0.76 cm/hr), CN = 60, Sandy Loam;
- B (0.38 < f < 0.76 cm/hr), CN = 70, Silt Loam;
- C (0.13 < f < 0.38 cm/hr), CN = 80, Clay Loam;
- D (0 < f < 0.13 cm/hr), CN = 90, Silty Clay.

In the TR-55 manual (SCS, 1986), the soil texture Clay Loam is classified as belonging to hydrologic group D due to poor drainage characteristics, typically created by a high water table. However, under the assumption that the soil is sufficiently drained it is herein classified as a C soil. The reason to adopt such an assumption in the present study is to provide examples of soils with a progressively decreasing of hydraulic conductivity values listed in Table 4.1.

4.4 Unit Hydrograph Development

The unit hydrographs in the present study were developed according to basic concepts of the SCS unit hydrograph technique but by using a different procedure. This new approach was derived to permit precise specification of the unit hydrograph duration rather than watershed characteristics such as a time of concentration and an average slope. By the new procedure, the unit hydrograph duration, t_r, varying from 5 min to 30 min with 5 minute intervals, can be generally expressed in hours as t_r = (5/60)*n*, where *n* =1, 2, …5. Then, basin lag, t_l, according to the relationship between components of the unit hydrograph, is equal to (45/120)n. The average slope, *Y*, is determined from equation 3.1 for any unit hydrograph duration, t_r:

$$Y^{0.5} = \frac{L^{0.8}\left[2540 - 22.86 * CN\right]^{0.7}}{14104 * CN^{0.7} * (45/120)n} \tag{4.4}$$

where *n* = 1,2,..5

In order to select the appropriate hydrograph duration that would cover the range of typical watershed slopes for curve numbers from 50 to 95, slope values were calculated by equation

4.4 for each *n*. The hydraulic length, *L*, is constant and equal to the length of longest pathway plane projection of the hypothetical watershed presented in Figure 3.5. Figure 4.12 demonstrates the resulting changes of the average slope, *Y*, with curve numbers for different unit hydrograph durations.

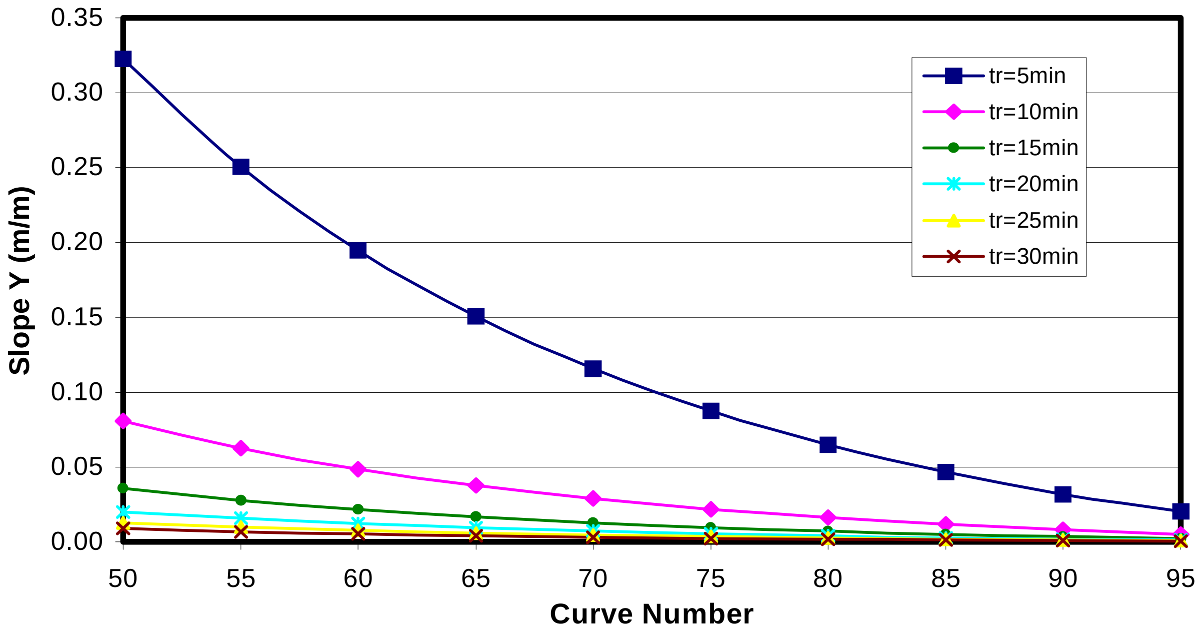

Figure 4.12 Variation in average watershed slope (Y) with curve (CN) numbers for various unit hydrograph durations (t_r).

As the plot in Figure 4.12 shows, the unit hydrograph durations of 5, 10, and 15 minutes encompass the range of typical watershed slopes. These durations were used to derive three unit hydrographs from the SCS dimensionless unit hydrograph. The computer program "3_SCS_Unit_Hydrograph.m", which is written in the Matlab language and available in Appendix C, calculates the unit hydrographs (Figure 4.13) and interpolates them with the interval of 5 minutes. Derived unit hydrographs, then, were convoluted into runoff hydrographs of three durations for different rainfall depths.

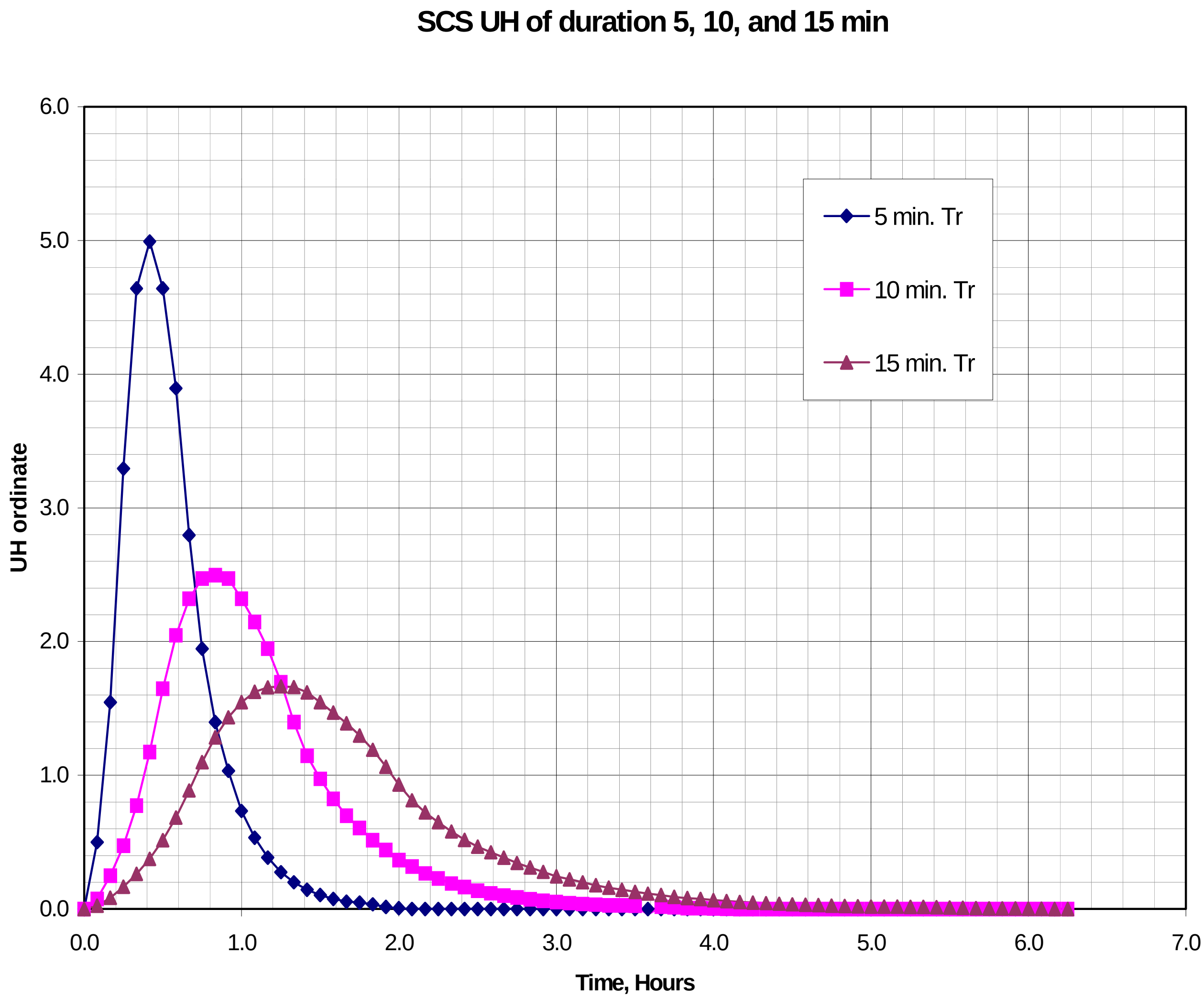

Figure 4.13 SCS unit hydrographs of duration 5, 10, 15 min

4.5 Runoff Hydrographs

The convolution process, which is used the present project, is based on the procedure described in Chow (1988) but involves more complicated calculations due to efforts to retain the fixed time increment (5 minutes) for various unit hydrograph durations (5, 10, 15 minutes). The convolution algorithm was programmed specifically for the project purposes to observe the differences in small resolution (5 minutes) runoff hydrographs of varied time of concentration. The programmed convolution process was verified by checking for mass conservation. The "UH_runoff_SCS.m" program performing the convolution process is listed in the Appendix C. Runoff hydrographs obtained for four selected soil types and four storm depths are presented in Figures A.1-48 (Appendix A) and discussed in Chapter 5.

CHAPTER 5

RESULTS AND ANALYSIS

5.1 Comparison

Four storm events with total precipitation depths of 8, 16, 24 and 32 cm were applied to the watershed, and runoff hydrographs of three different times of concentration, T_c, were obtained for each of four hydrological soil groups (A, B, C, and D). Each group is represented by one soil texture class and one curve number (Chapter 4.3). Plotted hydrographs for both the Green-Ampt and CN model are presented in pairs by Figures A.1 through A.48 (Appendix A) in four sets according to the soil texture class.

According to the obtained hydrographs, the CN model underestimates peak discharges as compared to the Green-Ampt model for all 48 cases. The plots show that the deviation between the two shapes in each pair of hydrographs varies depending on soil hydrologic group, storm depth, and time of concentration. The resulting peak discharges are summarized in Table A.1 (Appendix A). The following Figures 5.1 and Table 5.1 illustrate the differences in predicted peak discharges by both models for each curve number (60, 70, 80, and 90) as a function of rainfall depth.

The difference between the models is presented as ratio of the CN model discharge to the Green-Ampt model discharge. The ratio is larger for smaller storm depths. The SCS CN can underrate a peak discharge by as low as only 27 percent of the more physically realistic value predicted by the Green-Ampt model. However, for less permeable soils with high curve numbers the SCS CN model predictions are close to that of the Green-Ampt, and hydrograph shapes are almost identical.

Figure 5.2 and Table 5.2 demonstrate the relationship between the two models as a function of time of concentration, for corresponding curve numbers. According to the results, difference in time of concentration affects the peak discharge ratio only at lower rainfall depths. It can be seen from both Figure 5.2 and Table 5.2 that the hydrologic soil group D, represented by Silty Clay texture and curve number 90, is less likely to be influenced by time of concentration.

The accumulated infiltration plots, which are available in Figures B.1 through B.16 (Appendix B) illustrate the dependence of the CN infiltration on rainfall rate. At the same time, the plots show the same patterns of both models that are described in the above paragraphs: for smaller depths and curve numbers the SCS CN infiltration predictions are significantly different from those of the Green-Ampt model.

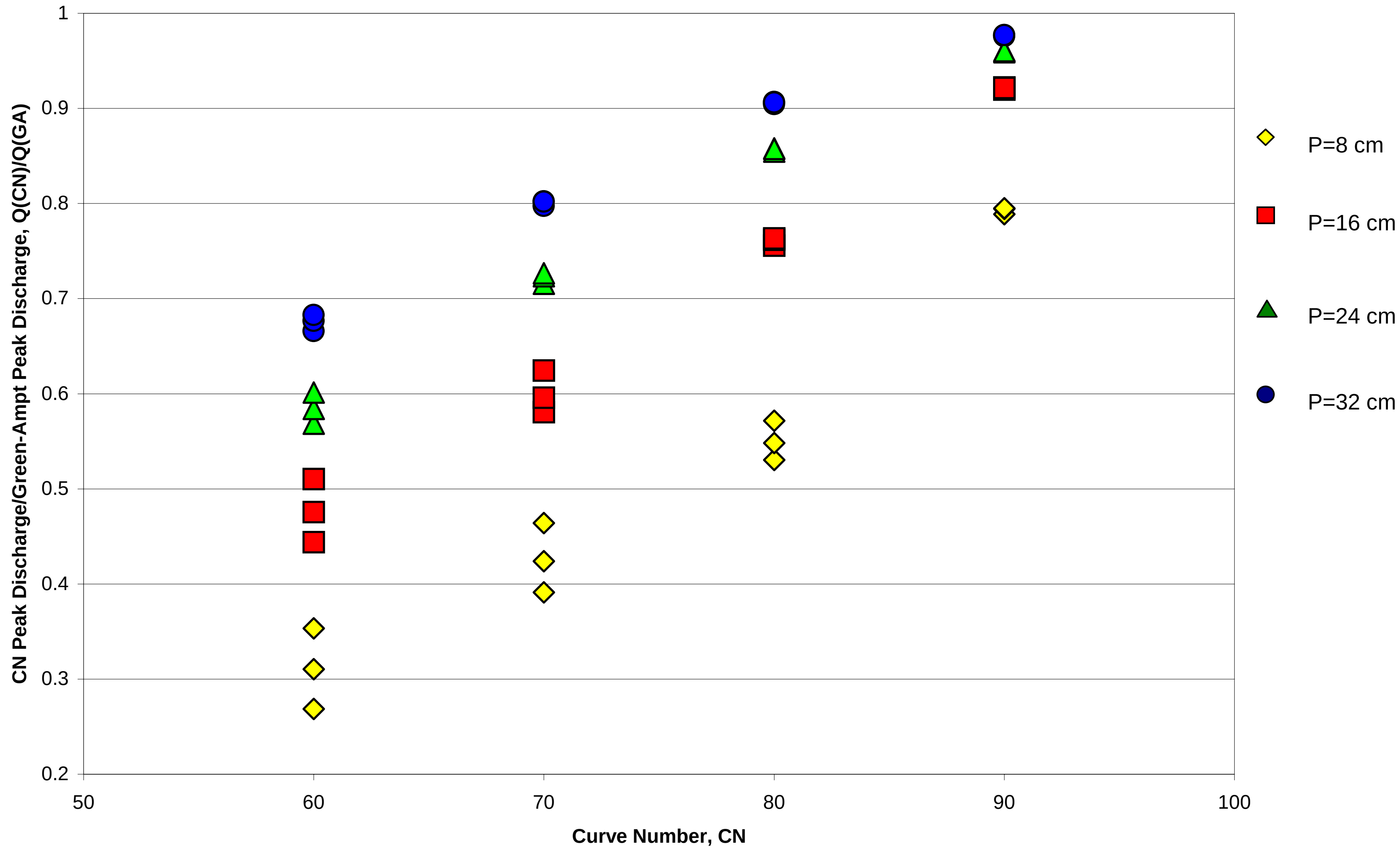

Figure 5.1 Ratio of Green-Ampt and SCS CN Peak Discharges versus Curve Number for Various Storm Depths, (P)

Table 5.1 SCS CN and Green-Ampt Peak Discharges for Various Storm Depths (P).

Curve number	CN peak discharges m^3/s				Green-Ampt peak discharges m^3/s				**CN prediction** % of Green-Ampt			
	P=8 cm	P=16 cm	P=24 cm	P=32 cm	P=8 cm	P=16 cm	P=24 cm	P=32 cm	P=8 cm	P=16 cm	P=24 cm	P=32 cm
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
60	1.088	9.252	20.426	32.911	4.052	20.832	35.928	49.438	26.851	44.412	56.851	66.570
	0.731	5.911	13.293	21.568	2.355	12.432	22.762	31.883	31.036	47.548	58.401	67.646
	0.573	4.444	9.963	16.102	1.623	8.709	16.571	23.587	35.329	51.028	60.120	68.265
70	3.214	13.983	26.779	40.207	8.218	24.077	37.426	50.437	39.108	58.078	71.553	79.717
	2.047	9.117	17.555	26.380	4.829	15.298	24.263	32.891	42.400	59.595	72.354	80.205
	1.547	6.829	13.109	19.722	3.332	10.936	18.041	24.602	46.417	62.439	72.663	80.162
80	6.199	18.958	32.507	46.079	11.690	25.089	38.038	50.960	53.026	75.564	85.460	90.423
	4.009	12.432	21.349	30.298	7.311	16.313	24.880	33.417	54.832	76.209	85.809	90.665
	3.011	9.287	16.002	22.769	5.267	12.165	18.663	25.131	57.168	76.338	85.743	90.601
90	9.923	23.482	36.869	50.105	12.582	25.526	38.444	51.357	78.865	91.993	95.904	97.563
	6.510	15.447	24.288	33.033	8.194	16.755	25.288	33.816	79.443	92.196	96.045	97.684
	4.865	11.619	18.317	24.944	6.119	12.611	19.074	25.532	79.502	92.137	96.028	97.698

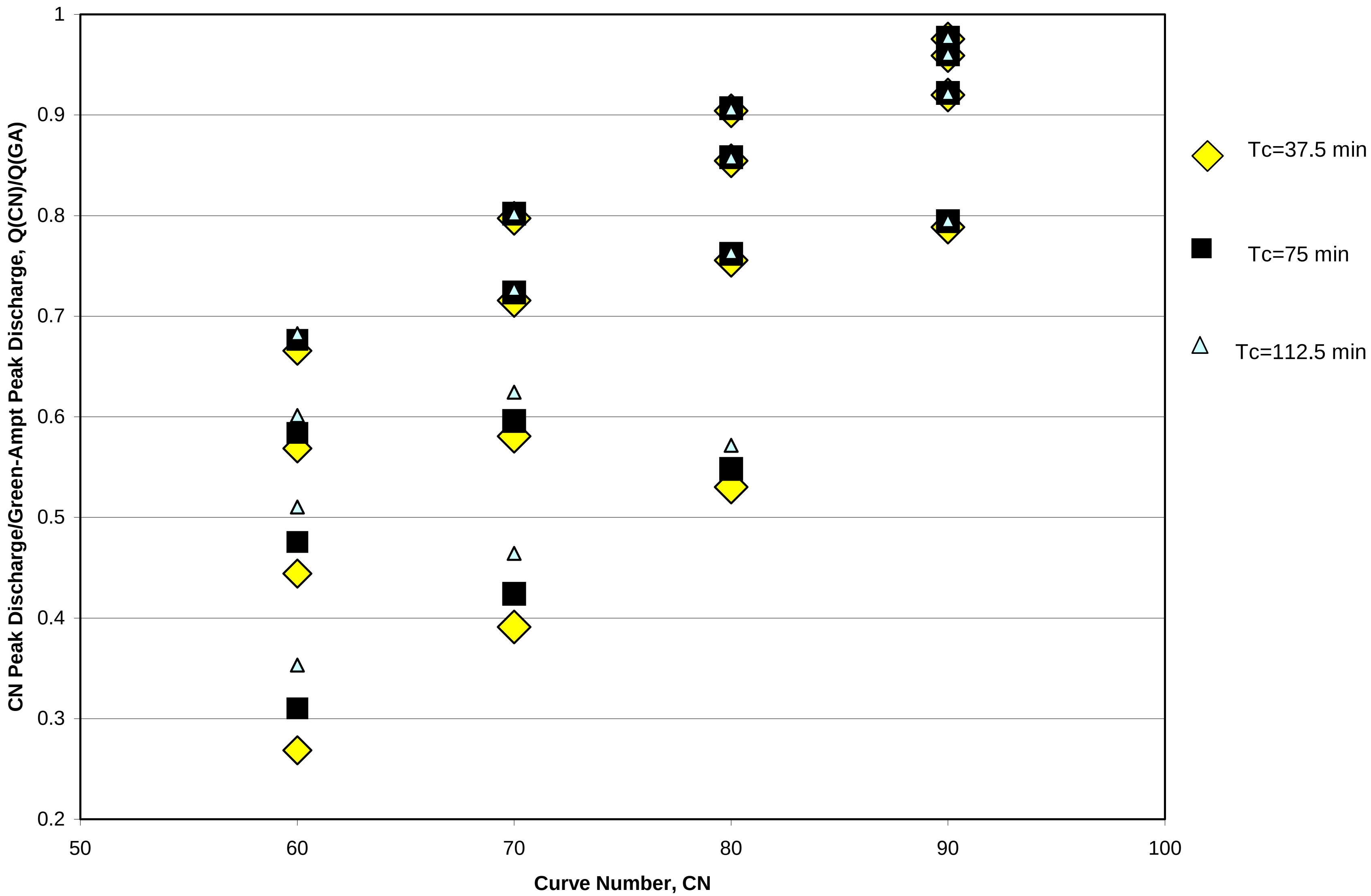

Figure 5.2 Ratio of Green-Ampt and SCS CN Peak Discharges versus Curve Numbers for Various Time of Concentration, Tc

Table 5.2 SCS CN and Green-Ampt Peak Discharges for Different Time of Concentration (Tc).

Curve number	CN peak discharges m^3/s			G-A peak discharges m^3/s			**CN peak discharge prediction % of Green-Ampt**		
	Tc=37.5min	Tc=75 min	Tc=112.5min	Tc=37.5min	Tc=75 min	Tc=112.5min	Tc=37.5min	Tc=75 min	Tc=112.5min
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
60	1.088	0.731	0.573	4.052	2.355	1.623	26.851	31.036	35.329
	9.252	5.911	4.444	20.832	12.432	8.709	44.412	47.548	51.028
	20.426	13.293	9.963	35.928	22.762	16.571	56.851	58.401	60.120
	32.911	21.568	16.102	49.438	31.883	23.587	66.570	67.646	68.265
70	3.214	2.047	1.547	8.218	4.829	3.332	39.108	42.400	46.417
	13.983	9.117	6.829	24.077	15.298	11.165	58.078	59.595	61.159
	26.779	17.555	13.109	37.426	24.263	18.041	71.553	72.354	72.663
	40.207	26.380	19.722	50.437	32.891	24.602	79.717	80.205	80.162
80	6.199	4.009	3.011	11.690	7.311	5.267	53.026	54.832	57.168
	18.958	12.432	9.287	25.089	16.313	12.165	75.564	76.209	76.338
	32.507	21.349	16.002	38.038	24.880	18.663	85.460	85.809	85.743
	46.079	30.298	22.769	50.960	33.417	25.131	90.423	90.665	90.601
90	9.923	6.510	4.865	12.582	8.194	6.119	78.865	79.443	79.502
	23.482	15.447	11.619	25.526	16.755	12.611	91.993	92.196	92.137
	36.869	24.288	18.317	38.444	25.288	19.074	95.904	96.045	96.028
	50.105	33.033	24.944	51.357	33.816	25.532	97.563	97.684	97.698

5.2 Impact Number

During the analysis of obtained data a new non-dimensional number was developed. This number was called "Impact Number" and defined as the following ratio:

$$\left(Q_p * T_c\right) / \left(A * Q\right)$$

where: Q_p = peak discharge;

T_c = time of concentration;

A = watershed area;

Q = direct runoff.

In order for the number to be non-dimensional, the units of all the involved parameters above must be consistent. Impact Number measures the tendency of watershed to have high peak discharge independently from the impact of influential parameters, such as T_c, A, and Q. Each of these latter parameters is included in the Impact Number in a manner that would tend to minimize the physical effect of that parameter on peak discharge. Namely, the increase in watershed area or runoff volume would proportionally increase the Q_p value and, thus, Q_p is divided by these two parameters in order to exclude their influence on it. In a similar way, time of concentration, T_c, which has an inversely proportional effect on peak discharge, is included as a product with Q_p. Hence, the Impact number represents the influence on a peak discharge by all other factors such as rainfall distribution and infiltration model, which are not involved in the ratio. In the present project one type of the rainfall distribution was used, and, therefore, only the infiltration model controls the peak discharge. The Green-Ampt and the SCS CN infiltration models produce a different Impact Number when the all other parameters are the same.

In Figure 5.3 the Impact Number values for three values of T_c are plotted against the runoff-rainfall ratio, Q(24) / P(24). The differences in the Impact Number values for smaller runoff-rainfall ratios are dramatic and they continuously diminish as the runoff-rainfall ratio reaches the highest values.

The developed Impact Number can be a valuable tool for comparisons of different infiltration model performance. For the case of using the Green-Ampt infiltration model within the SCS CN procedure, the number can serve as a criterion of usefulness of such a substitution or, in other words, show when the substitution is necessary.

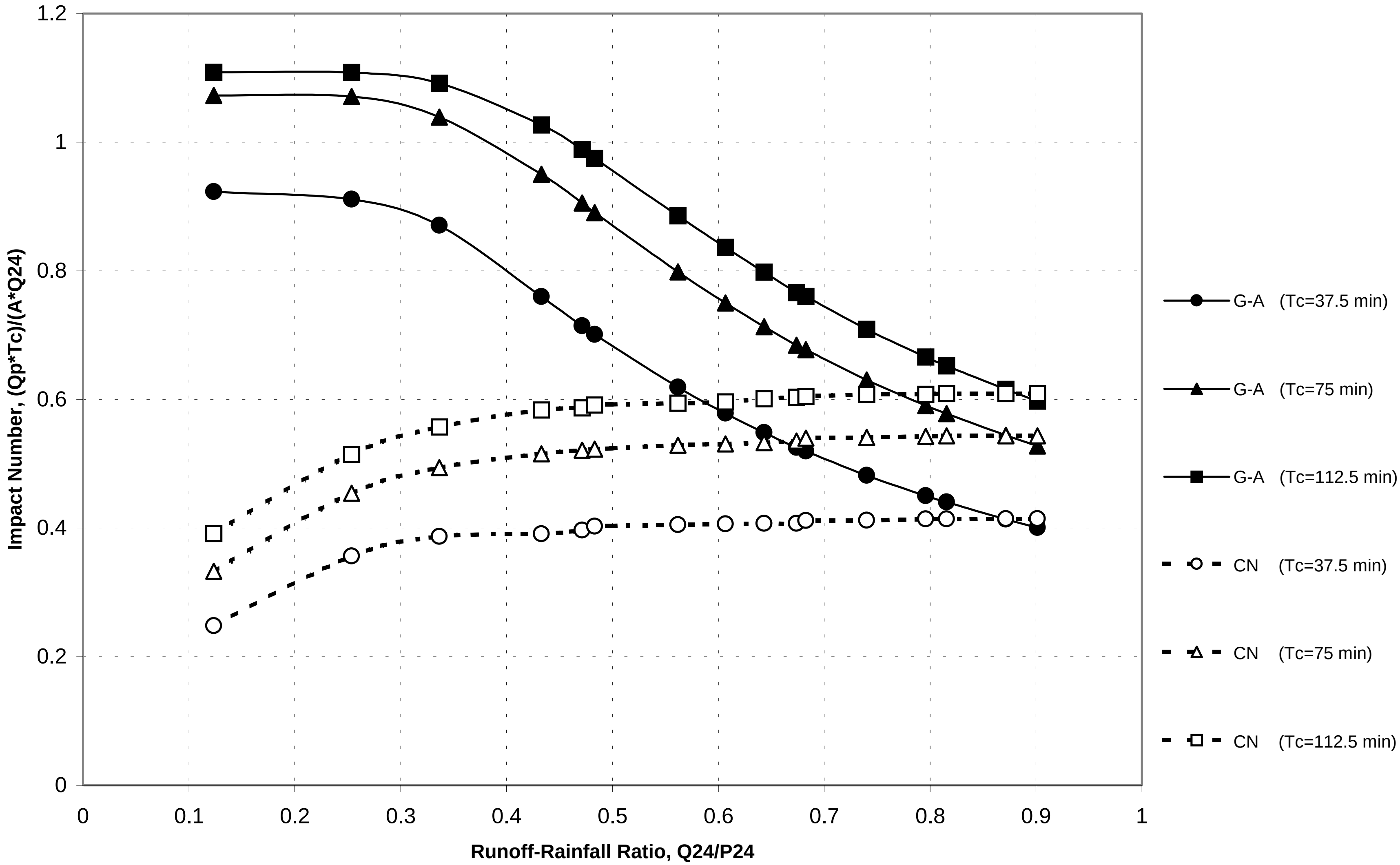

Figure 5.3 Runoff-Rainfall Ratio versus Impact Number

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

In order to improve the SCS CN method and support the use of the physically based Green-Ampt model to attain a realistic infiltration distribution by means of the SCS CN method, the present study demonstrates the differences in peak discharge predictions between the SCS CN infiltration model and the Green-Ampt model within the SCS CN method. The investigation develops a technique, which allows obtainment of the Green-Ampt parameters by relating them to the SCS Curve Numbers. The procedure involves estimation of the Green-Ampt hydraulic conductivity from the SCS Curve number and from soil texture class throughout a series of developed plots and calculation of the wetting front capillary pressure from derived empirical relationships between the Green-Ampt parameters (see Appendix D for the example).

The comparison of the infiltration distribution shows that the SCS CN infiltration model underpredicts peak discharges with respect to the Green-Ampt model, especially for small depth rainfall events and low values of time of concentration. The future application of the Green-Ampt model can amend the evaluation of runoff peak discharges up to 77 percent for some cases of A, B, and C soils. The study also shows that for soils of hydrological group D, especially for high rainfall depth, peak discharges predicted by both models are close, with differences in predictions varying from 20 to only 2 percent. The general result of the thesis is that the Green-Ampt model can, in many instances, be successfully applied to estimate infiltration distribution and so considerably improve the SCS CN method.

Additional study is necessary to prove the procedure of estimation of the Green-Ampt parameters developed by the present investigation. The procedure needs to be tested on different historical rainfall-runoff events from different locations. Also, it would be useful to compare the infiltration models when using different rainfall distributions.

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APPENDIX A

RUNOFF HYDROGRAPHS

Table A.1 Peak Discharges by Green-Ampt and SCS CN Models

Soil (CN)	Precipitation depth, P cm	Time of con centration,Tc min	Green-Ampt model Time to peak, Tp hr	Green-Ampt model Peak dis-charge m^3/s	CN model Time to peak, Tp hr	CN model Peak dis-charge m^3/s
Sandy Loam (60)	8	37.5	12.166667	4.051869	12.333333	1.087984
		75.0	12.583333	2.354940	12.916667	0.730880
		112.5	12.916667	1.623130	13.416667	0.573431
	16	37.5	12.166667	20.832437	12.250000	9.252121
		75.0	12.583333	12.431846	12.666667	5.911102
		112.5	12.916667	8.709013	13.083333	4.444041
	24	37.5	12.166667	35.928212	12.250000	20.425631
		75.0	12.583333	22.761902	12.583333	13.293170
		112.5	12.916667	16.571228	13.083333	9.962629
	32	37.5	12.166667	49.438465	12.166667	32.911135
		75.0	12.583333	31.883202	12.583333	21.567861
		112.5	12.916667	23.587133	13.000000	16.101682
Silt Loam (70)	8	37.5	12.166667	8.217968	12.250000	3.213899
		75.0	12.500000	4.828843	12.750000	2.047448
		112.5	12.833333	3.332372	13.166667	1.546777
	16	37.5	12.166667	24.076940	12.250000	13.983348
		75.0	12.583333	15.297937	12.583333	9.116813
		112.5	12.916667	11.165222	13.083333	6.828540
	24	37.5	12.166667	37.425710	12.166667	26.779341
		75.0	12.583333	24.262769	12.583333	17.555048
		112.5	12.916667	18.041426	13.000000	13.109370
	32	37.5	12.166667	50.436680	12.166667	40.206784
		75.0	12.583333	32.891142	12.583333	26.380411
		112.5	12.916667	24.602090	12.916667	19.721624
Clay Loam (80)	8	37.5	12.166667	11.690058	12.250000	6.198747
		75.0	12.583333	7.310835	12.583333	4.008664
		112.5	12.916667	5.267056	13.083333	3.011078
	16	37.5	12.166667	25.088505	12.166667	18.957836
		75.0	12.583333	16.313459	12.583333	12.432265
		112.5	12.916667	12.165138	13.000000	9.286651
	24	37.5	12.166667	38.037954	12.166667	32.507191
		75.0	12.583333	24.879675	12.583333	21.349017
		112.5	12.916667	18.663300	12.916667	16.002410
	32	37.5	12.166667	50.959596	12.166667	46.079044
		75.0	12.583333	33.417164	12.583333	30.297669
		112.5	12.916667	25.131004	12.916667	22.768829
Silty Clay (90)	8	37.5	12.166667	12.582272	12.166667	9.922960
		75.0	12.583333	8.194290	12.583333	6.509812
		112.5	12.916667	6.118920	12.916667	4.864641
	16	37.5	12.166667	25.526104	12.166667	23.482284
		75.0	12.583333	16.754705	12.583333	15.447172
		112.5	12.916667	12.610957	12.916667	11.619358
	24	37.5	12.166667	38.444199	12.166667	36.869463
		75.0	12.583333	25.288423	12.583333	24.288157
		112.5	12.916667	19.074449	12.916667	18.316760
	32	37.5	12.166667	51.356736	12.166667	50.105275
		75.0	12.583333	33.816430	12.583333	33.033179
		112.5	12.916667	25.531962	12.916667	24.944278

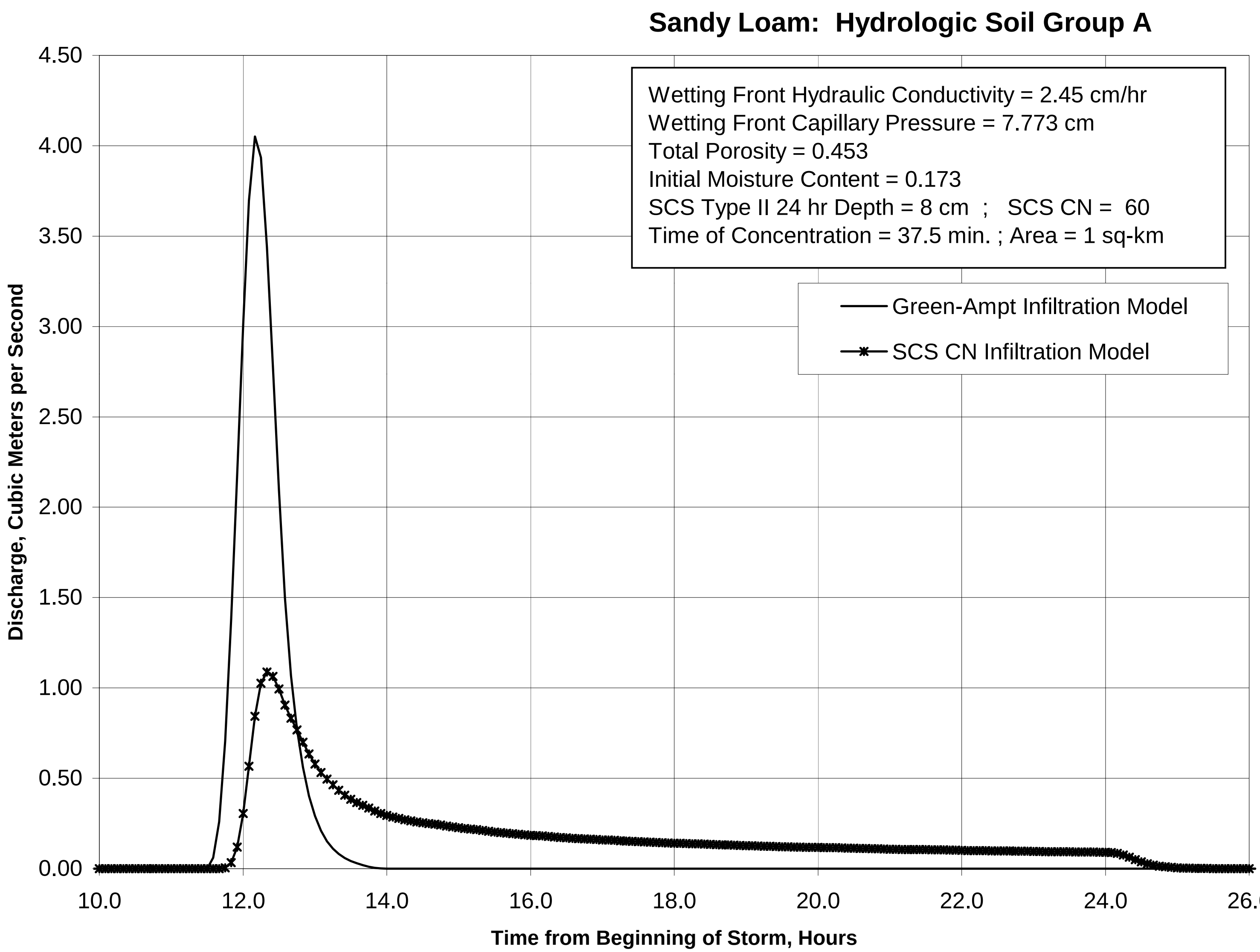

Figure A.1 Equal Volume Runoff Hydrographs, 8 cm Storm Depth, CN = 60, Tc = 37.5 min.

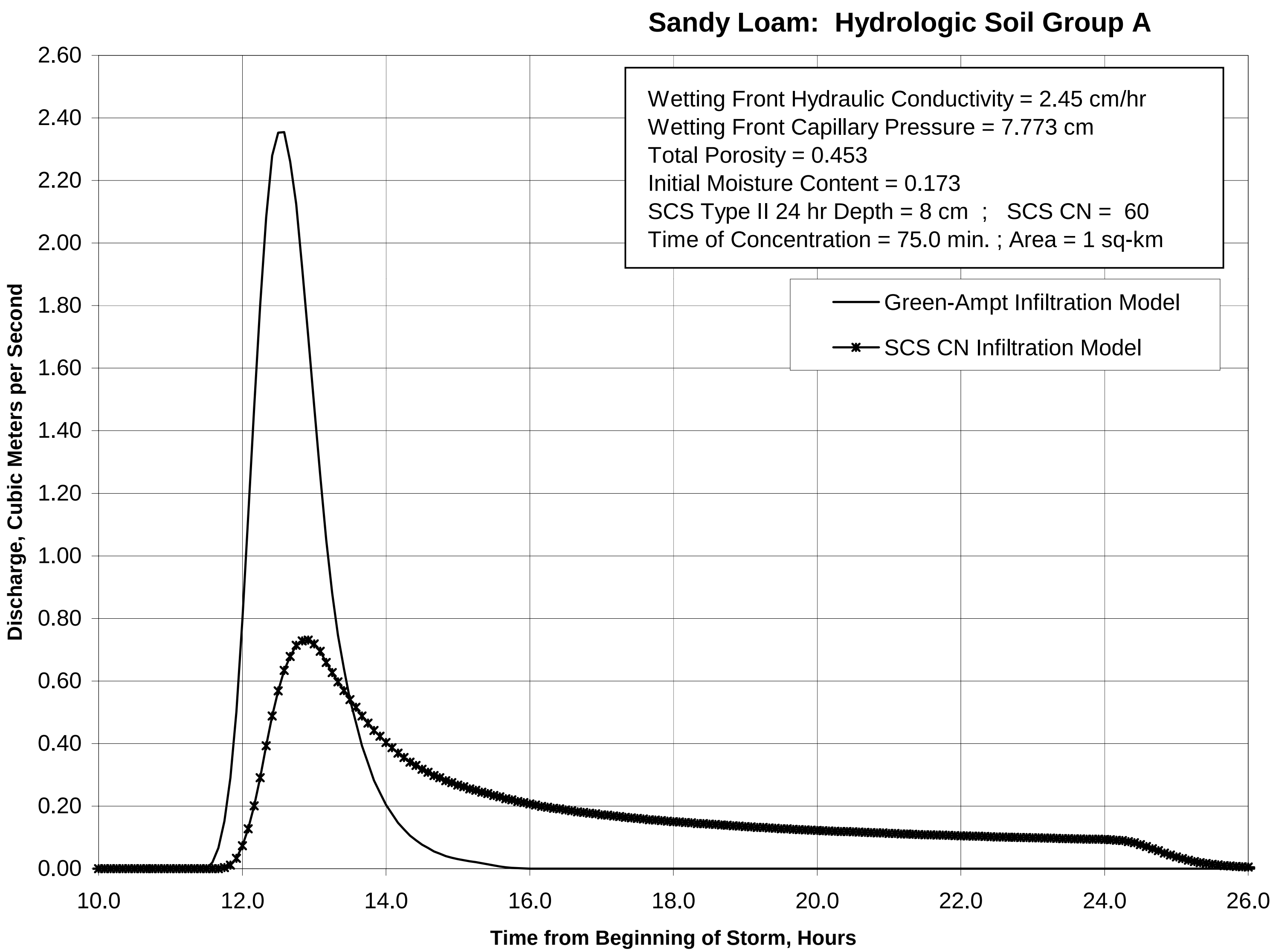

Figure A.2 Equal Volume Runoff Hydrographs, 8 cm Storm Depth, CN = 60, Tc = 75.0 min.

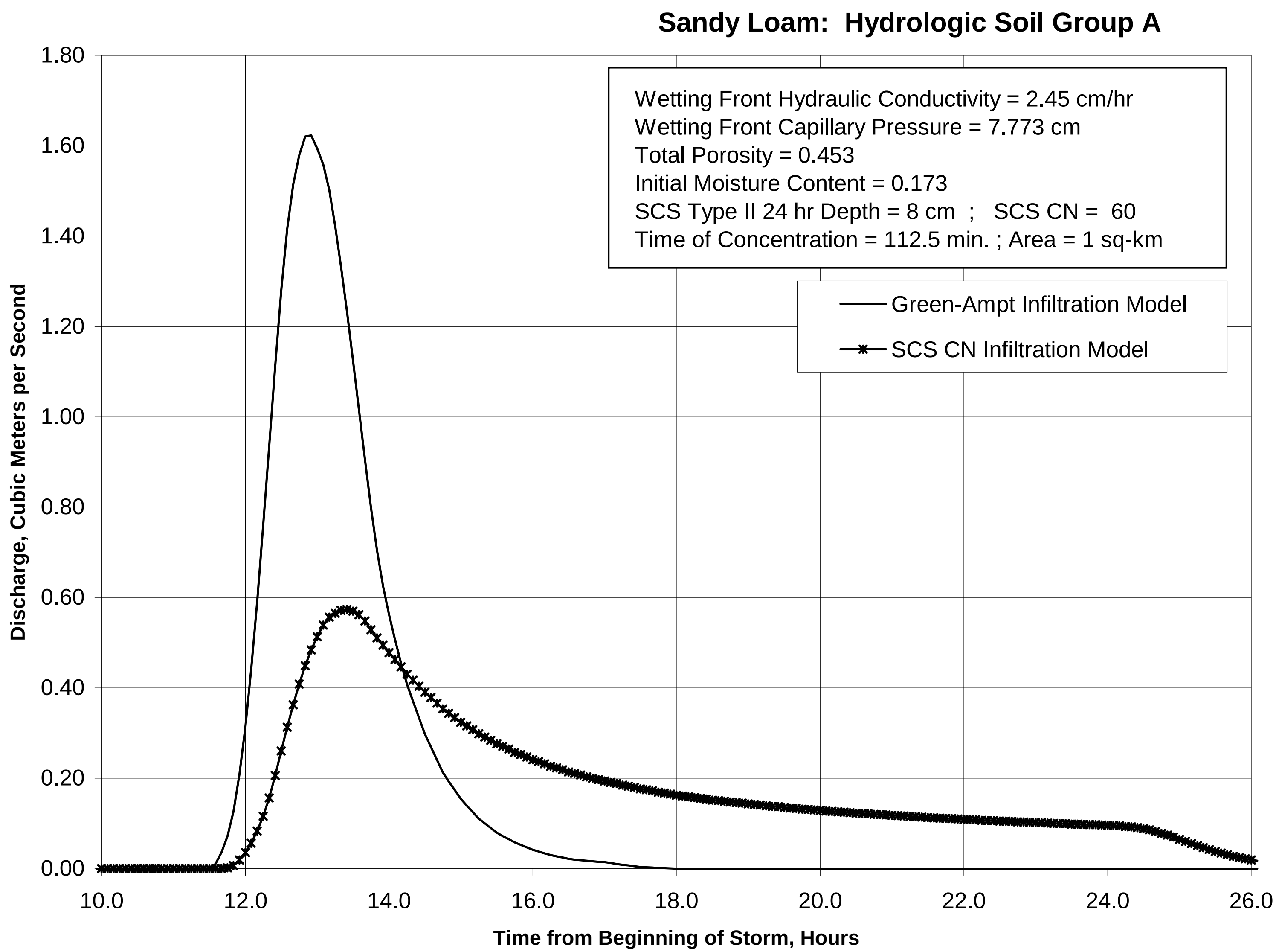

Figure A.3 Equal Volume Runoff Hydrographs, 8 cm Storm Depth, CN = 60, Tc = 112.5 min.

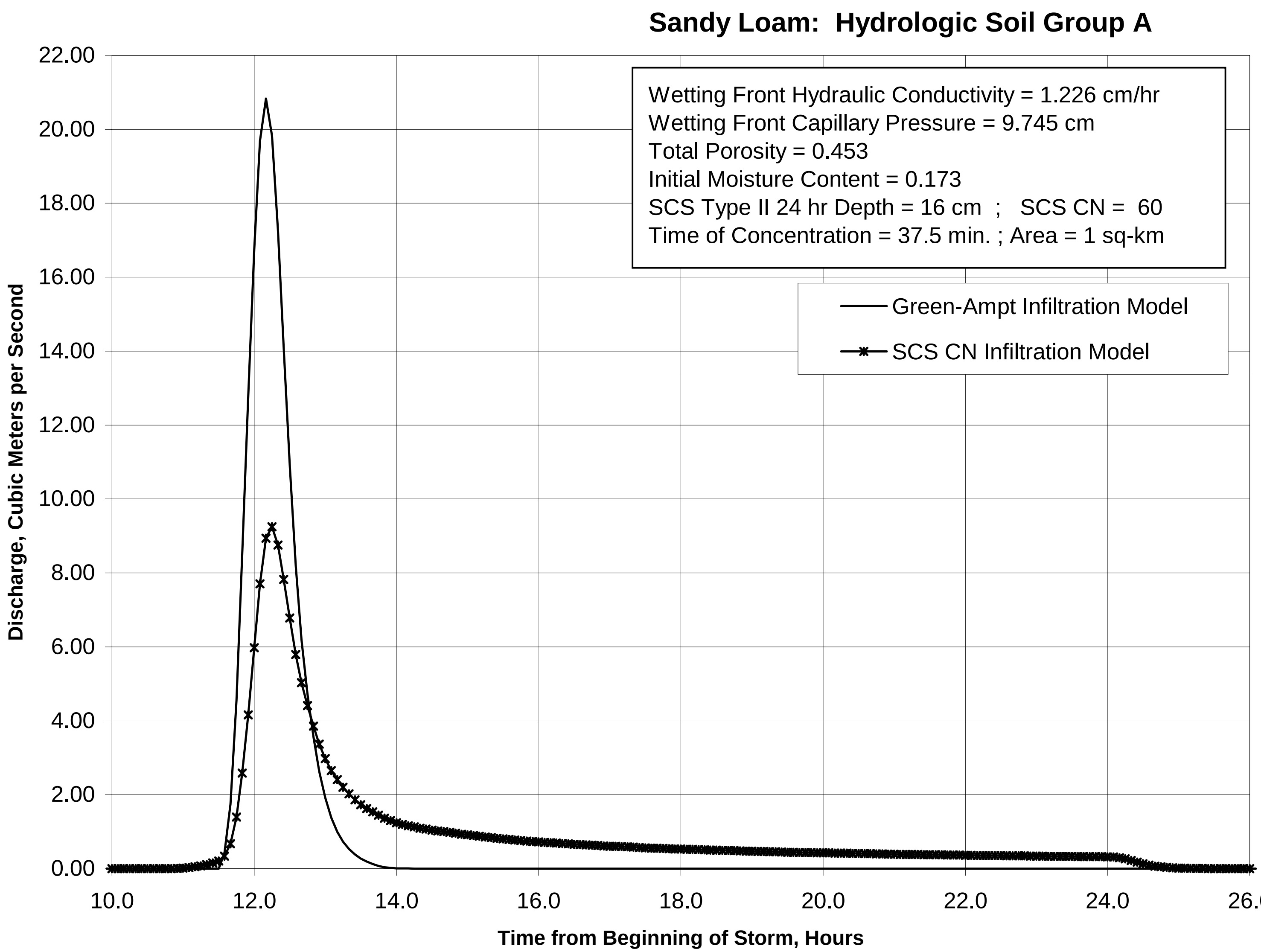

Figure A.4 Equal Volume Runoff Hydrographs, 16 cm Storm Depth, CN = 60, Tc = 37.5 min.

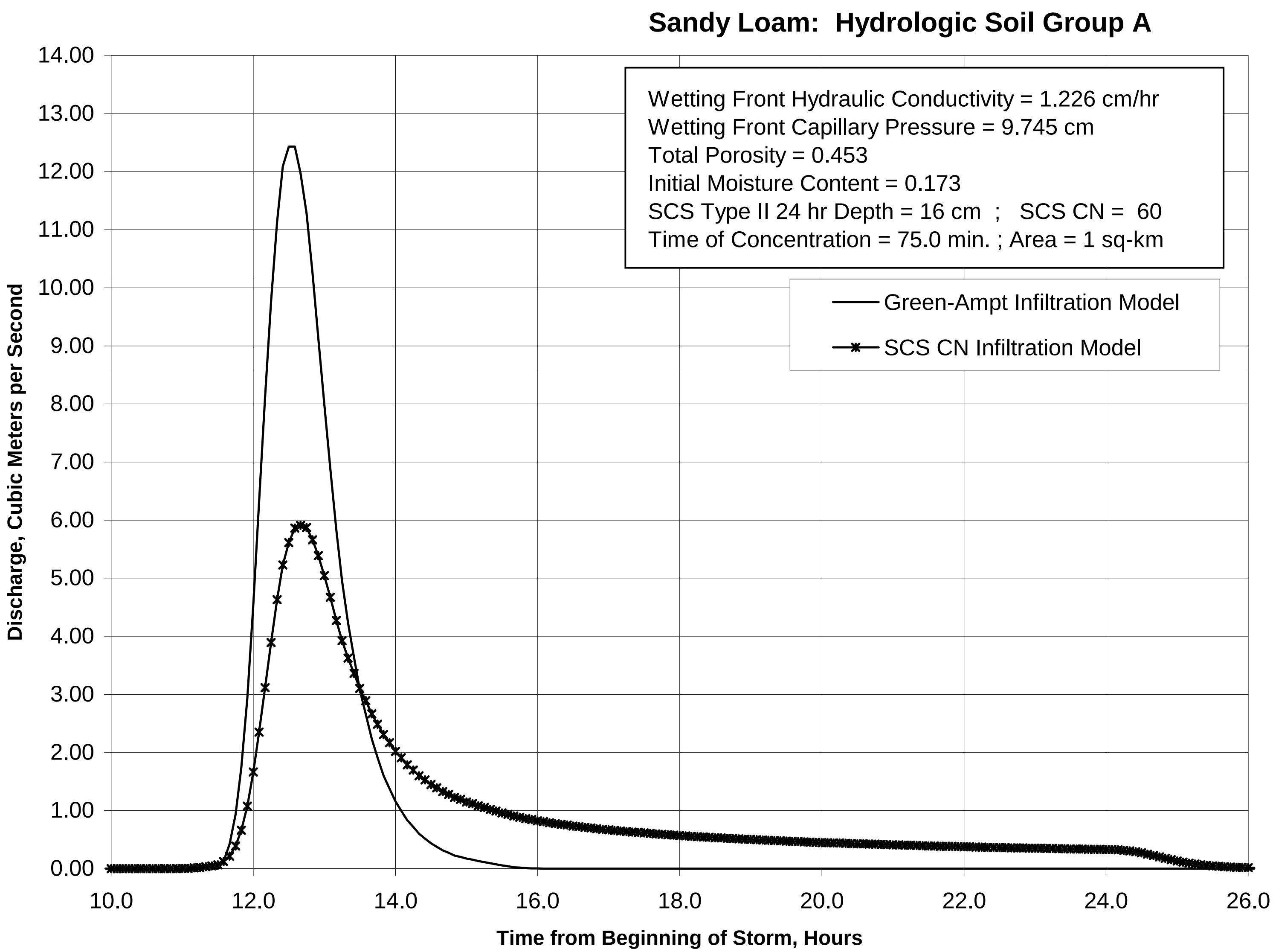

Figure A.5   Equal Volume Runoff Hydrographs, 16 cm Storm Depth, CN = 60, Tc = 75.0 min.

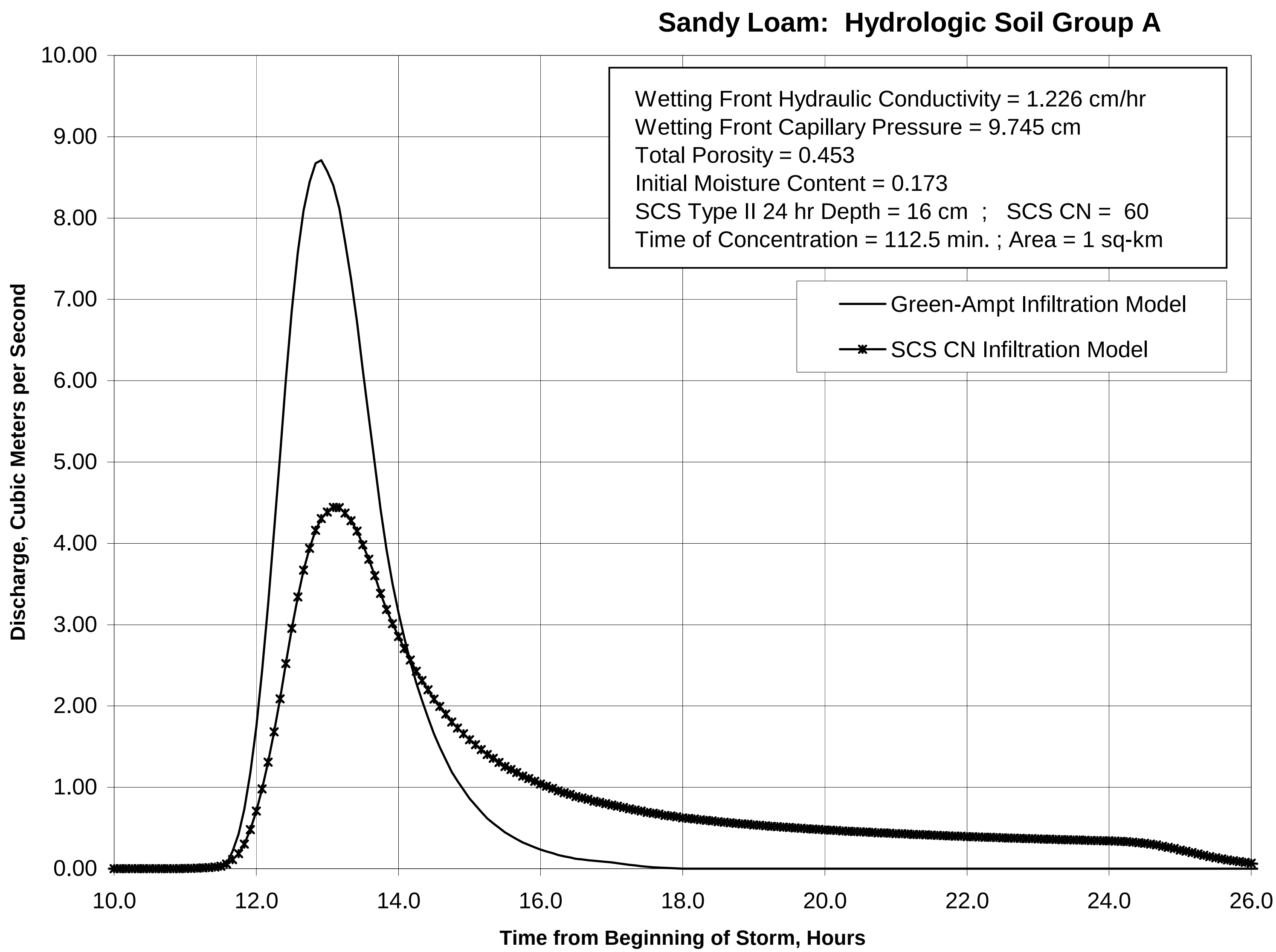

Figure A.6 Equal Volume Runoff Hydrographs, 16 cm Storm Depth, CN = 60, Tc = 112.5 min.

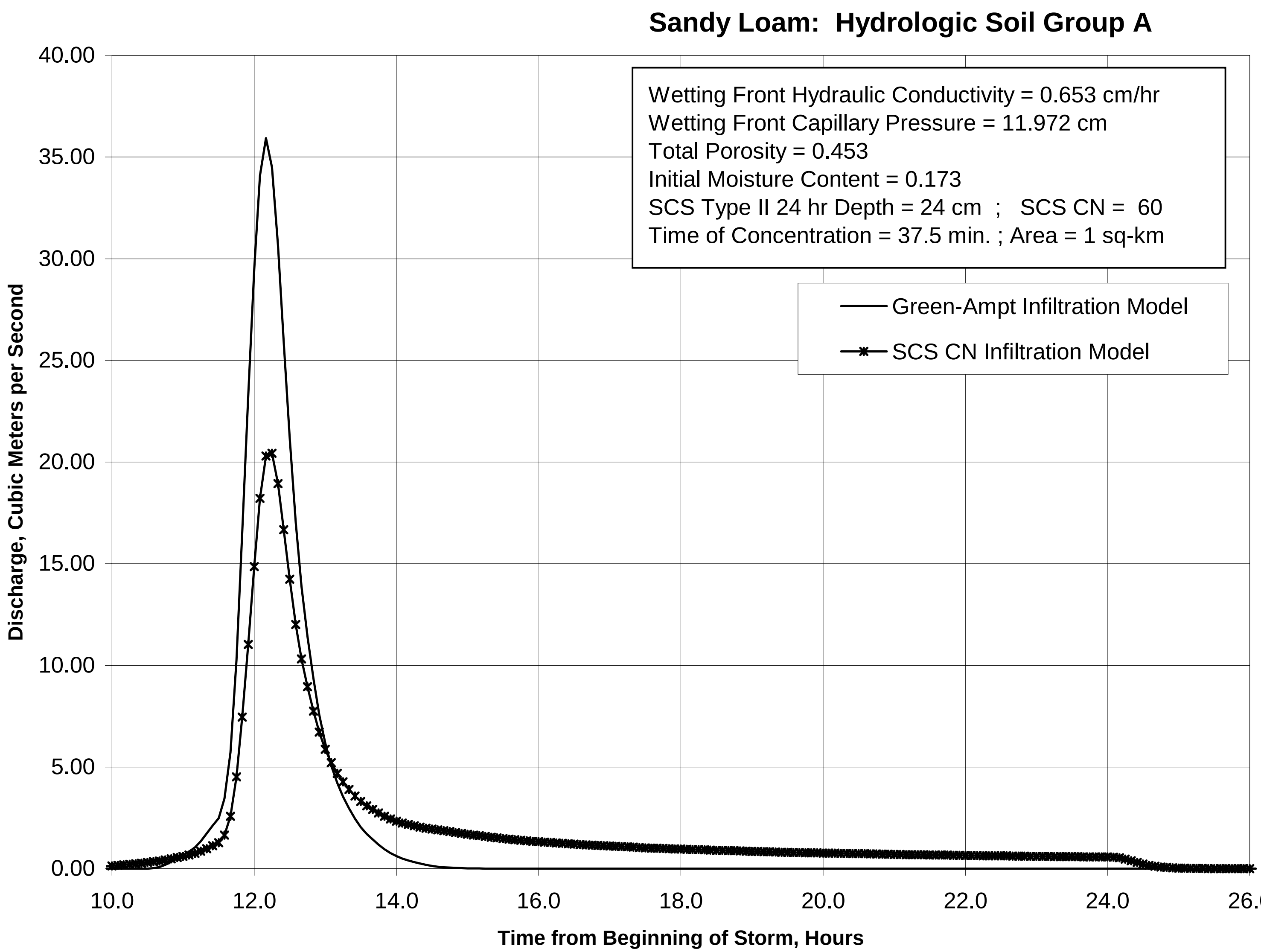

Figure A.7 Equal Volume Runoff Hydrographs, 24 cm Storm Depth, CN = 60, Tc = 37.5 min.

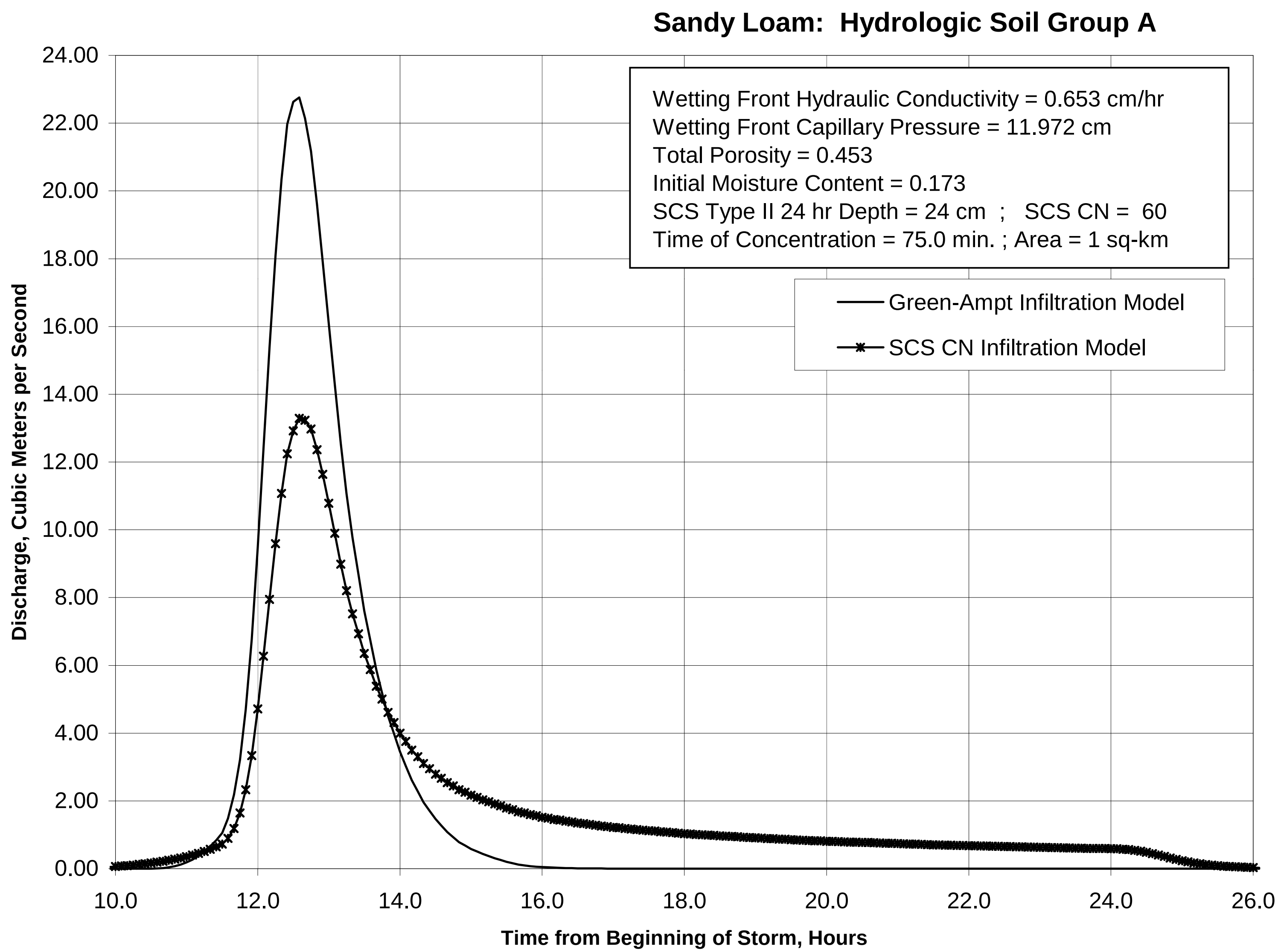

Figure A.8 Equal Volume Runoff Hydrographs, 24 cm Storm Depth, CN = 60, Tc = 75.0 min.

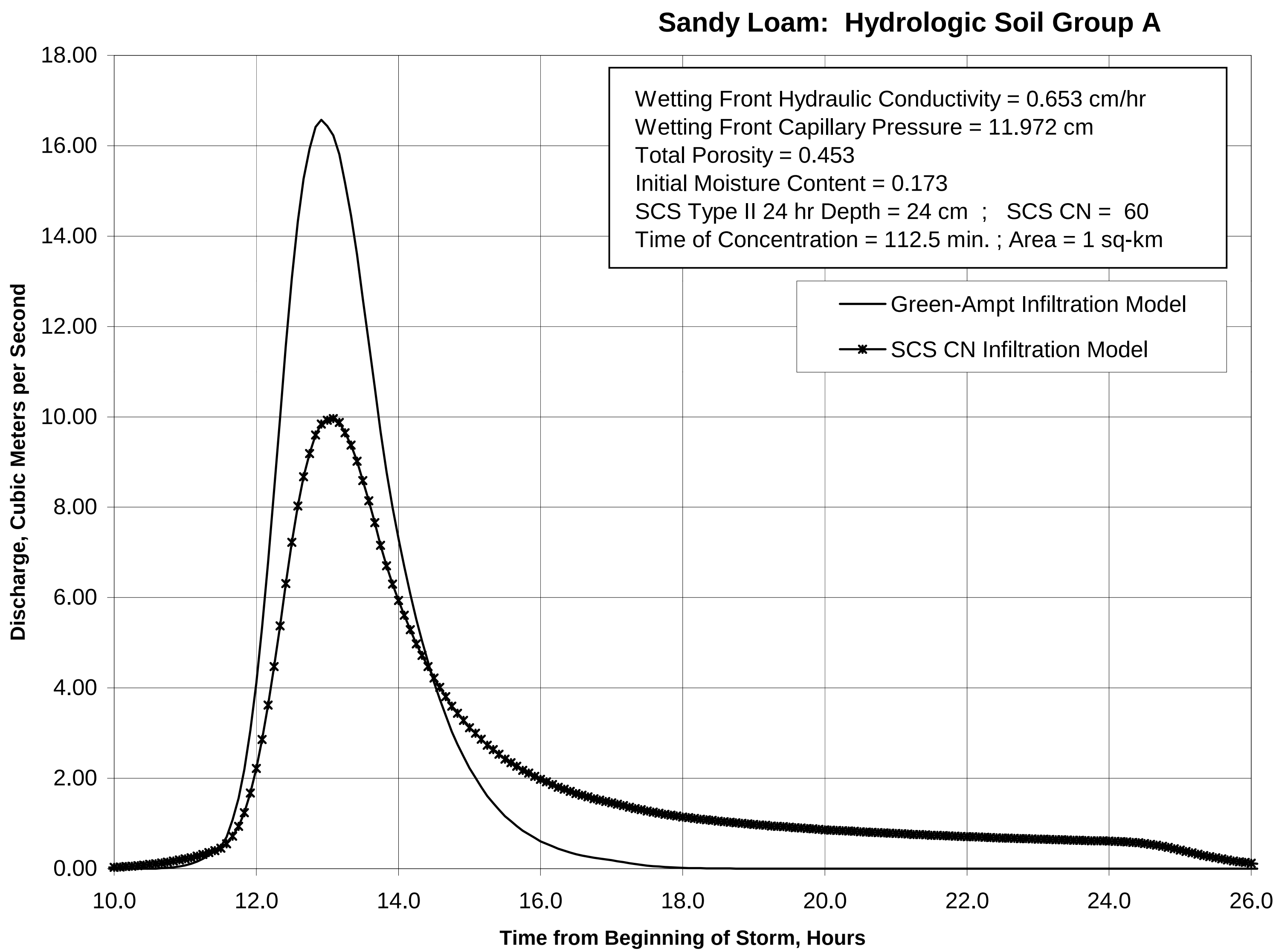

Figure A.9 Equal Volume Runoff Hydrographs, 24 cm Storm Depth, CN = 60, Tc = 112.5 min.

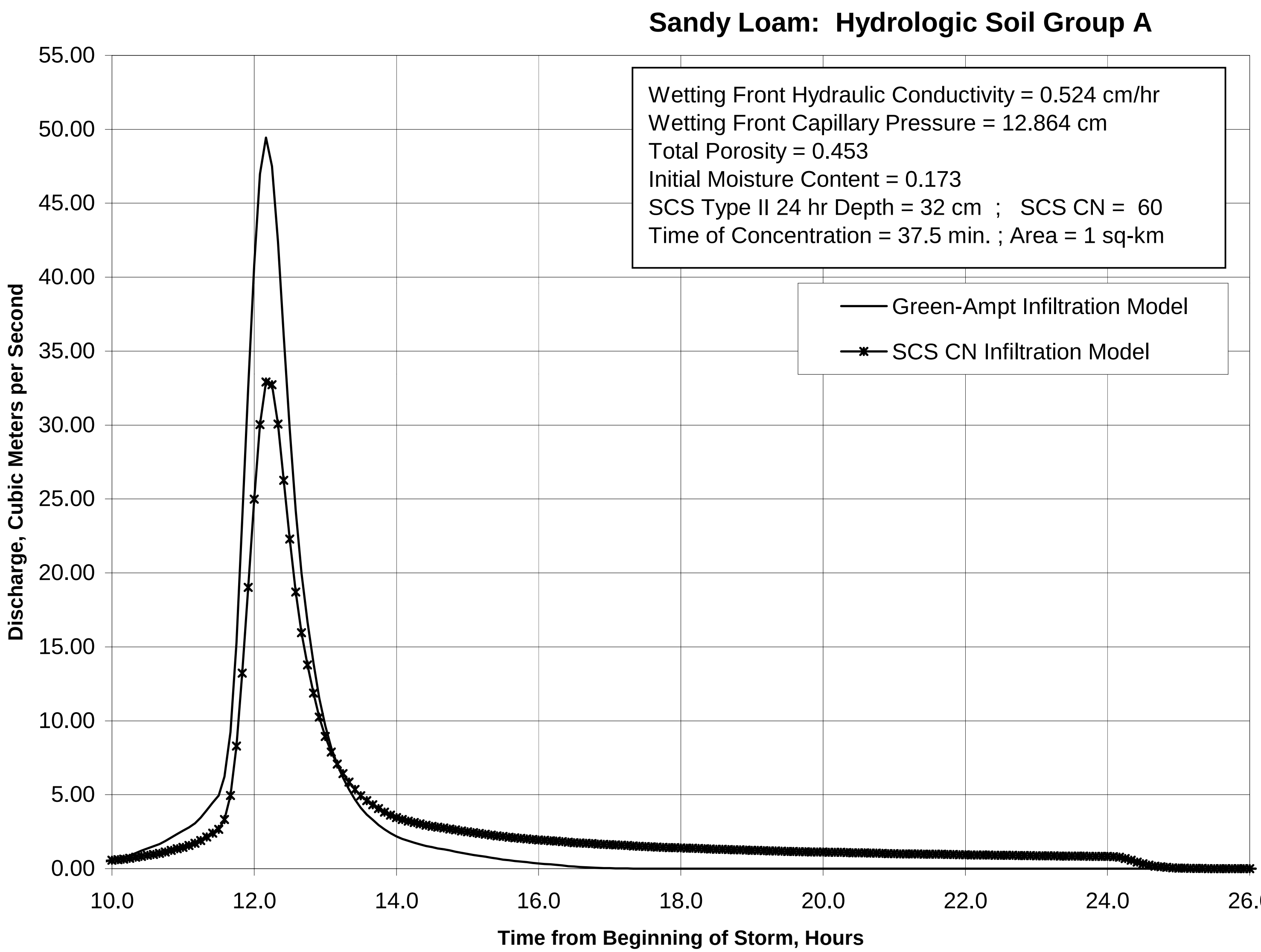

Figure A.10 Equal Volume Runoff Hydrographs, 32 cm Storm Depth, CN = 60, Tc = 37.5 min.

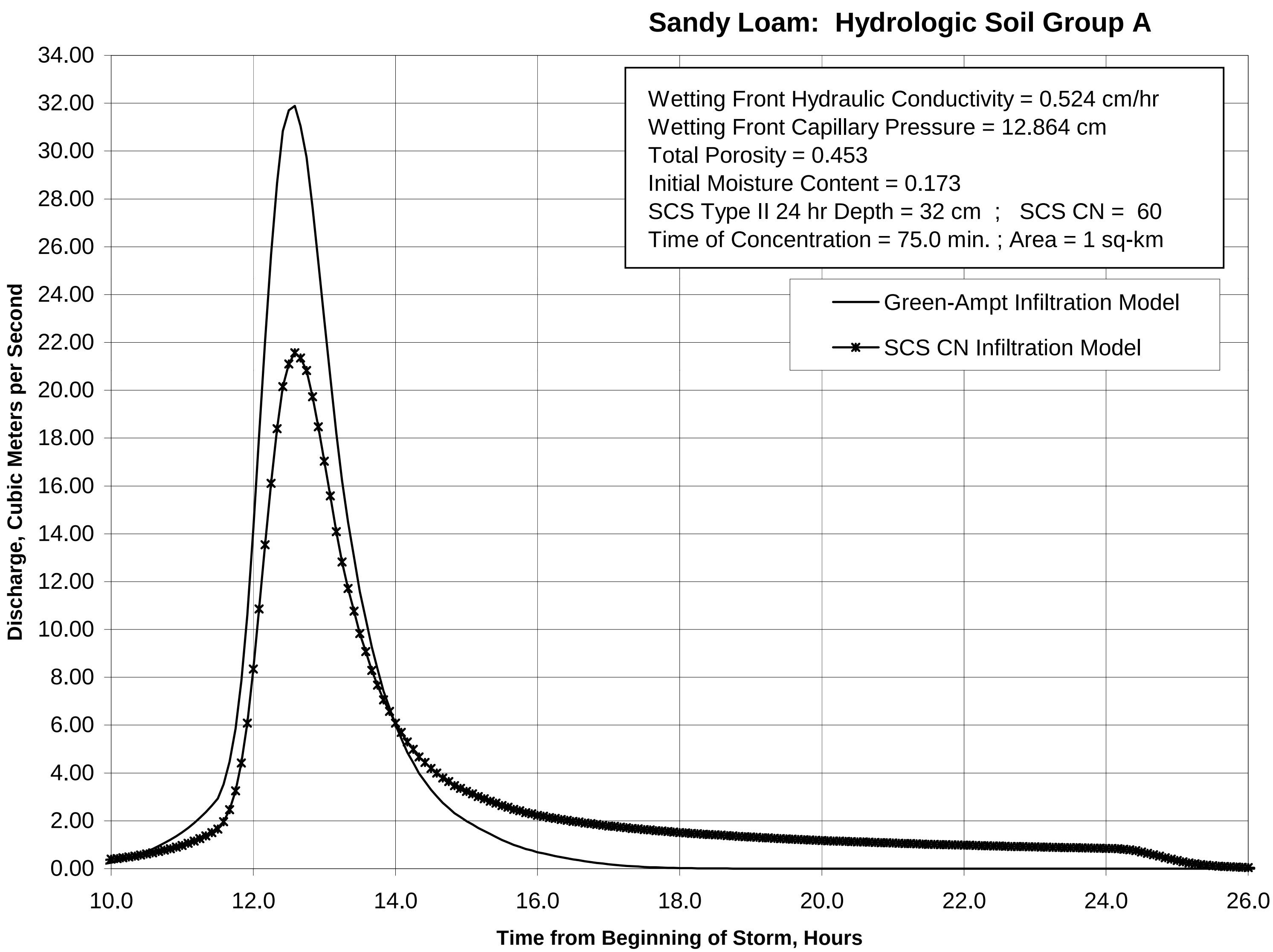

Figure A.11 Equal Volume Runoff Hydrographs, 32 cm Storm Depth, CN = 60, Tc = 75.0 min.

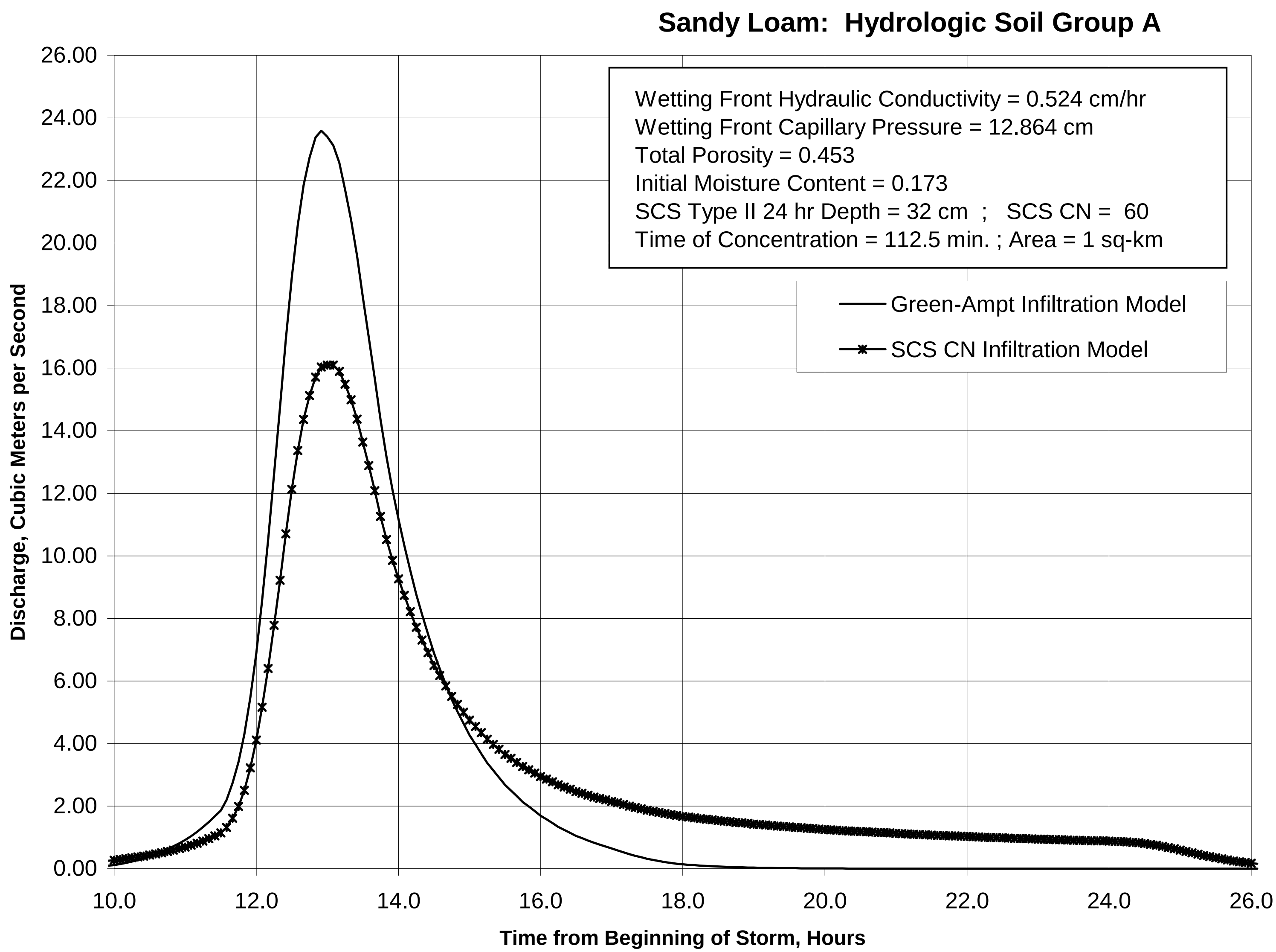

Figure A.12 Equal Volume Runoff Hydrographs, 32 cm Storm Depth, CN = 60, Tc = 112.5 min.

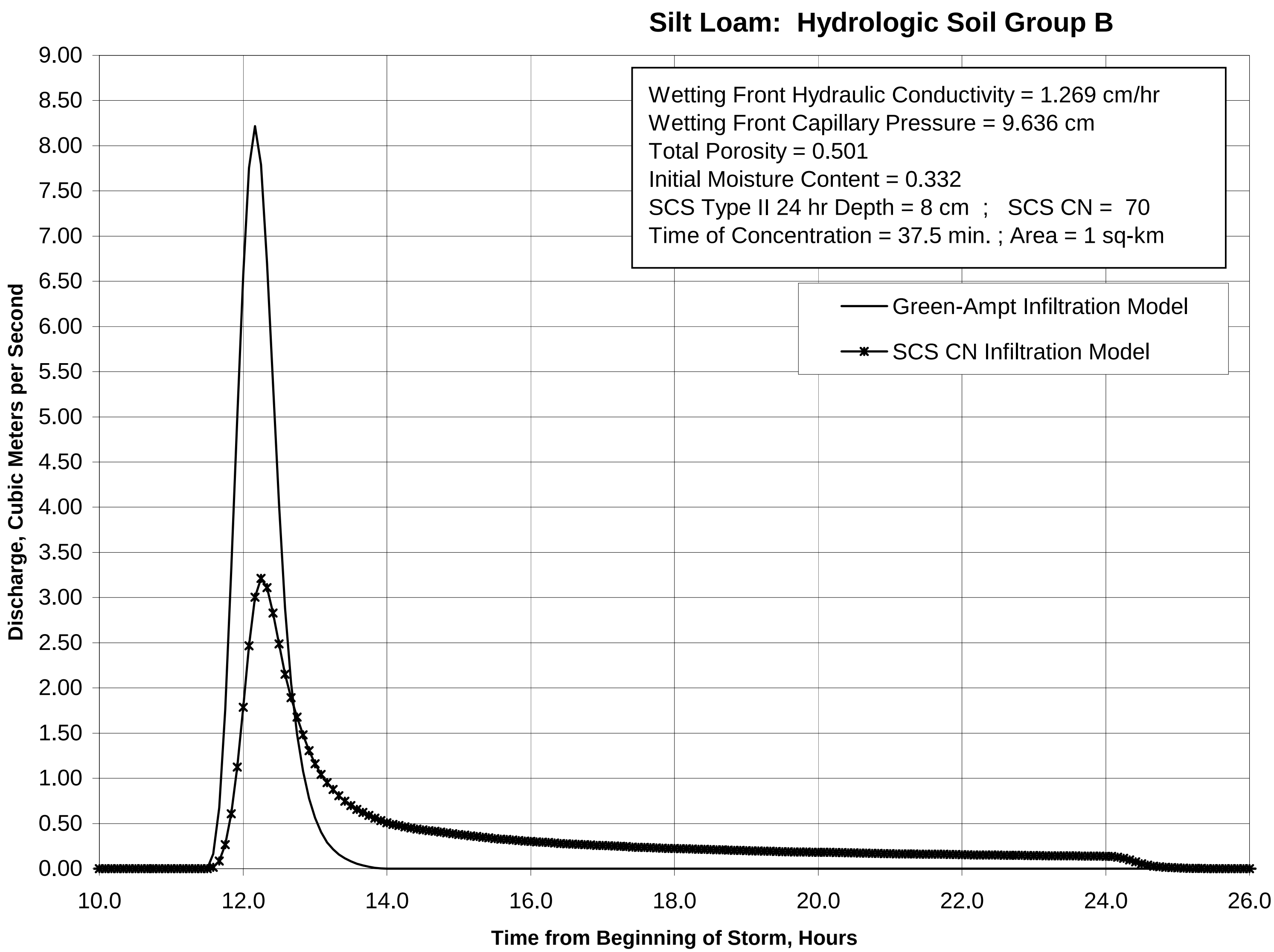

Figure A.13   Equal Volume Runoff Hydrographs, 8 cm Storm Depth, CN = 70, Tc = 37.5 min.

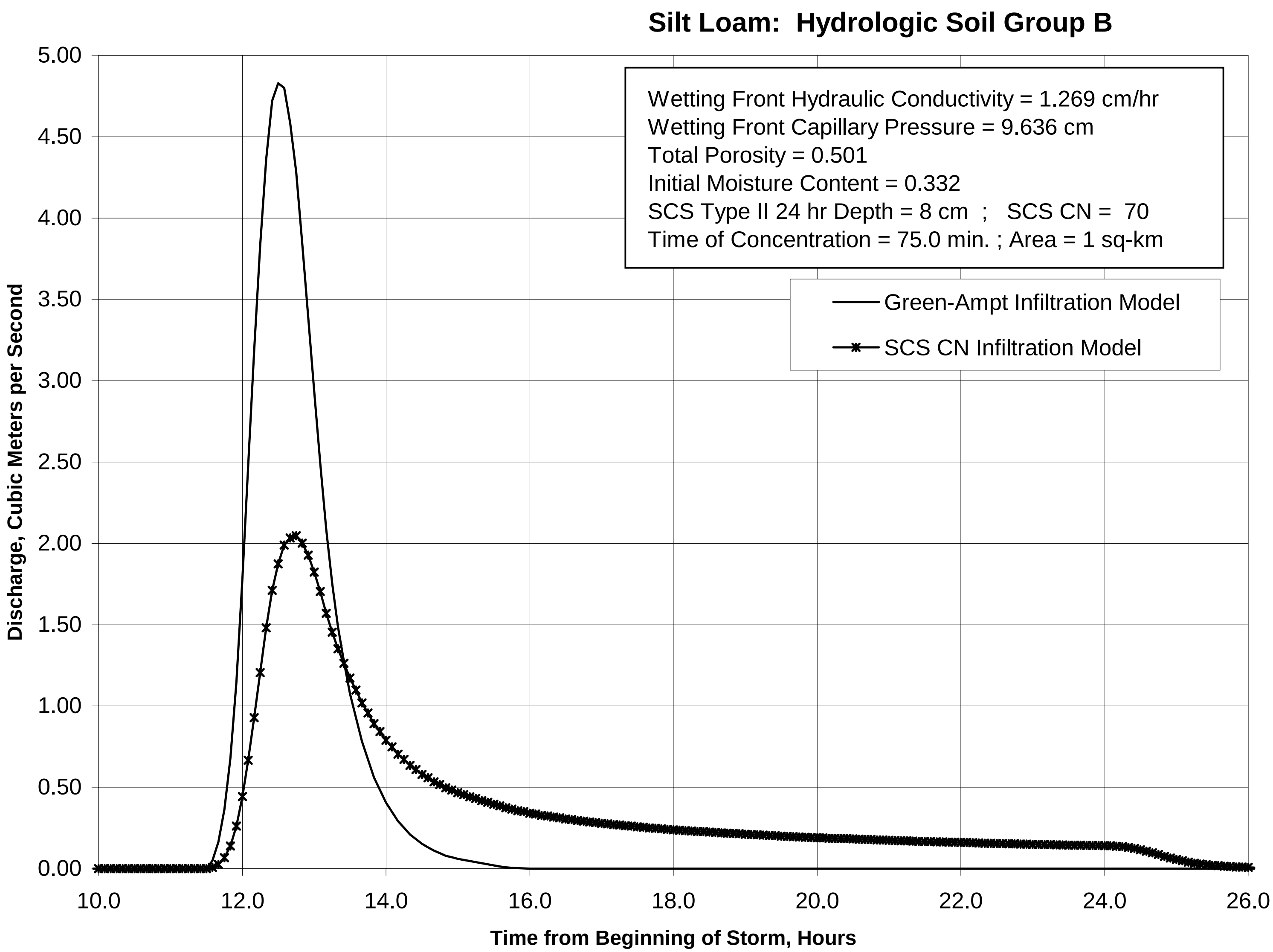

Figure A.14   Equal Volume Runoff Hydrographs, 8 cm Storm Depth, CN = 70, Tc = 75.0 min.

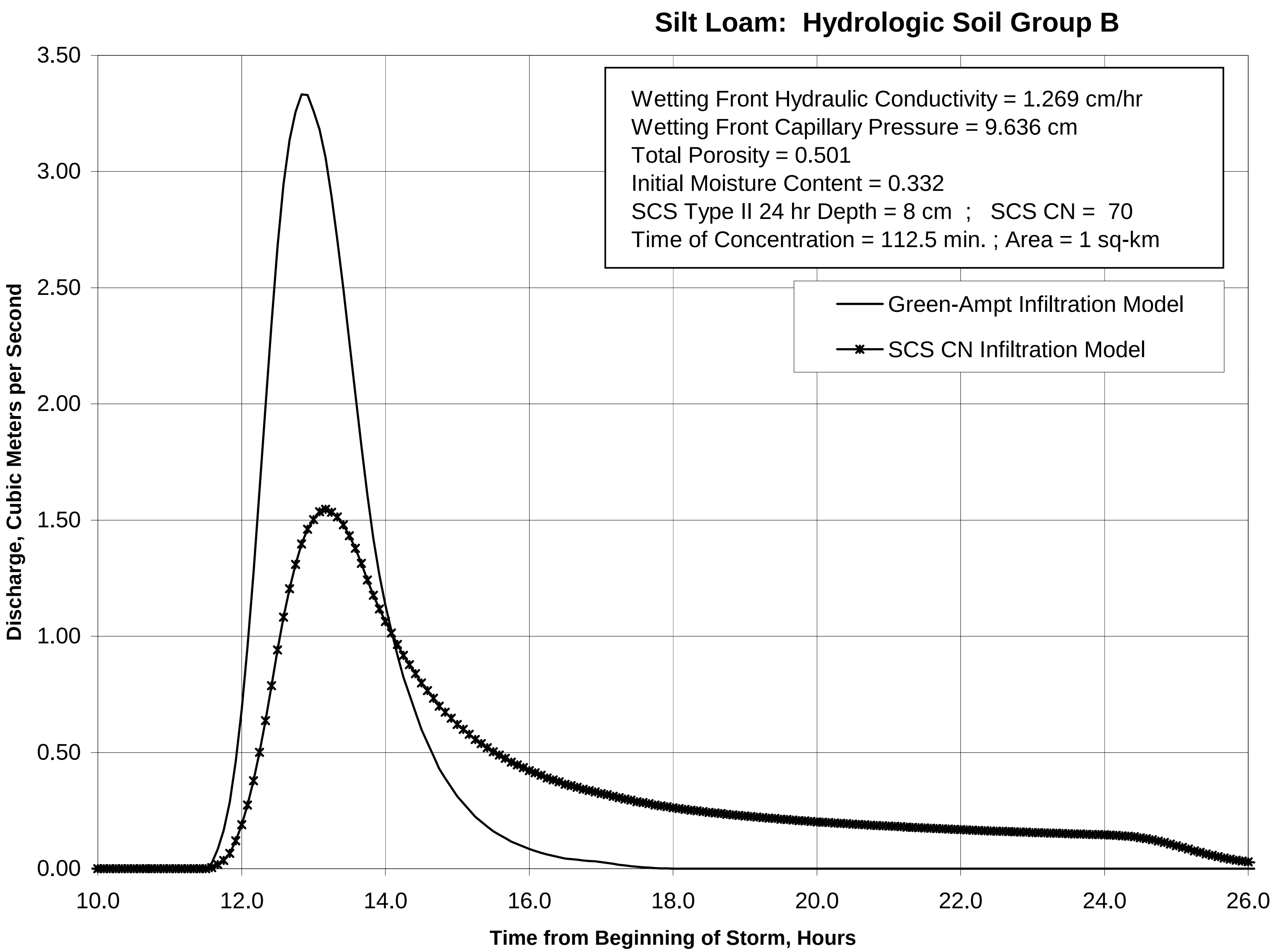

Figure A.15 Equal Volume Runoff Hydrographs, 8 cm Storm Depth, CN = 70, Tc = 112.5 min.

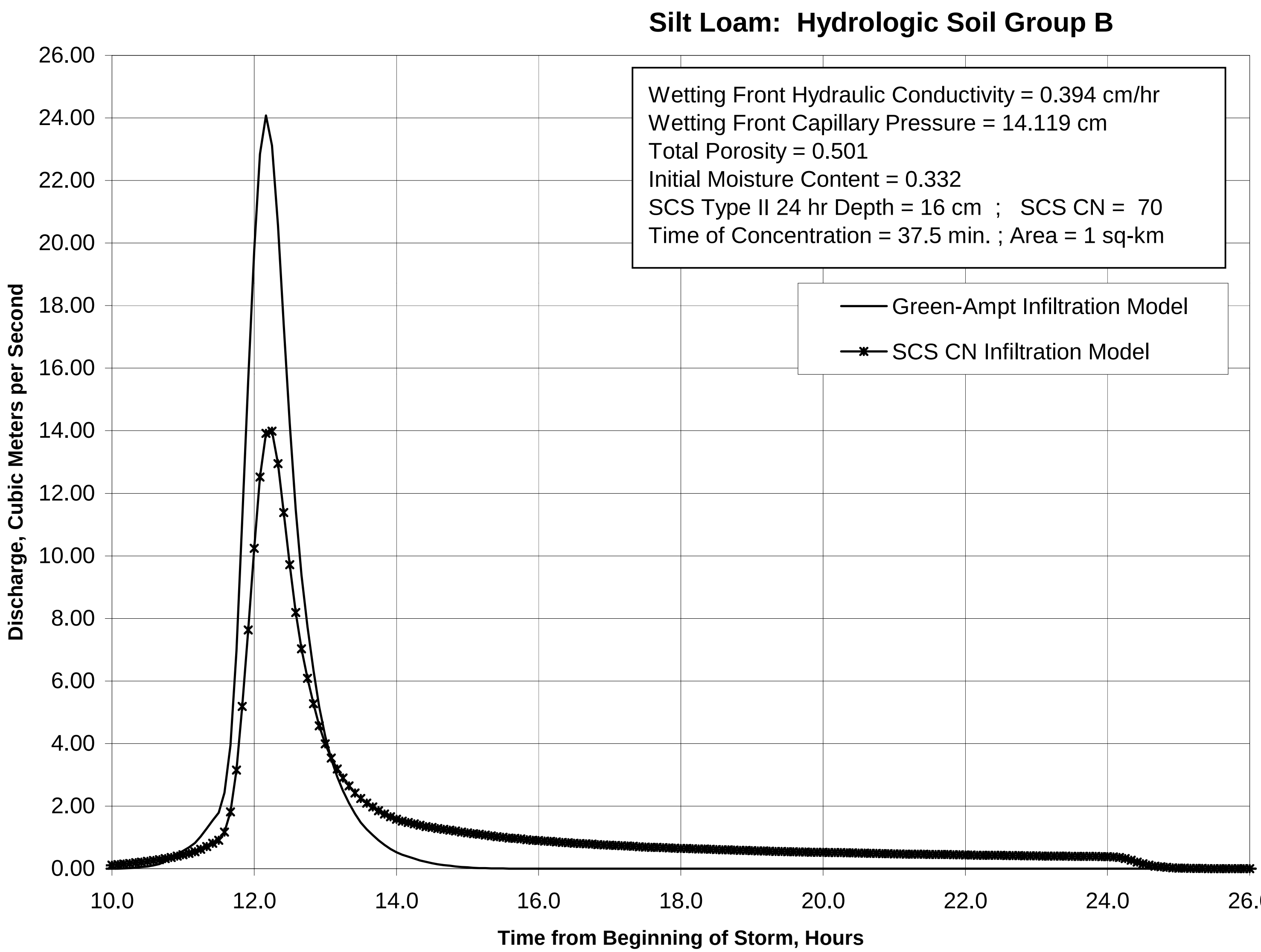

Figure A.16 Equal Volume Runoff Hydrographs, 16 cm Storm Depth, CN = 70, Tc = 37.5 min.

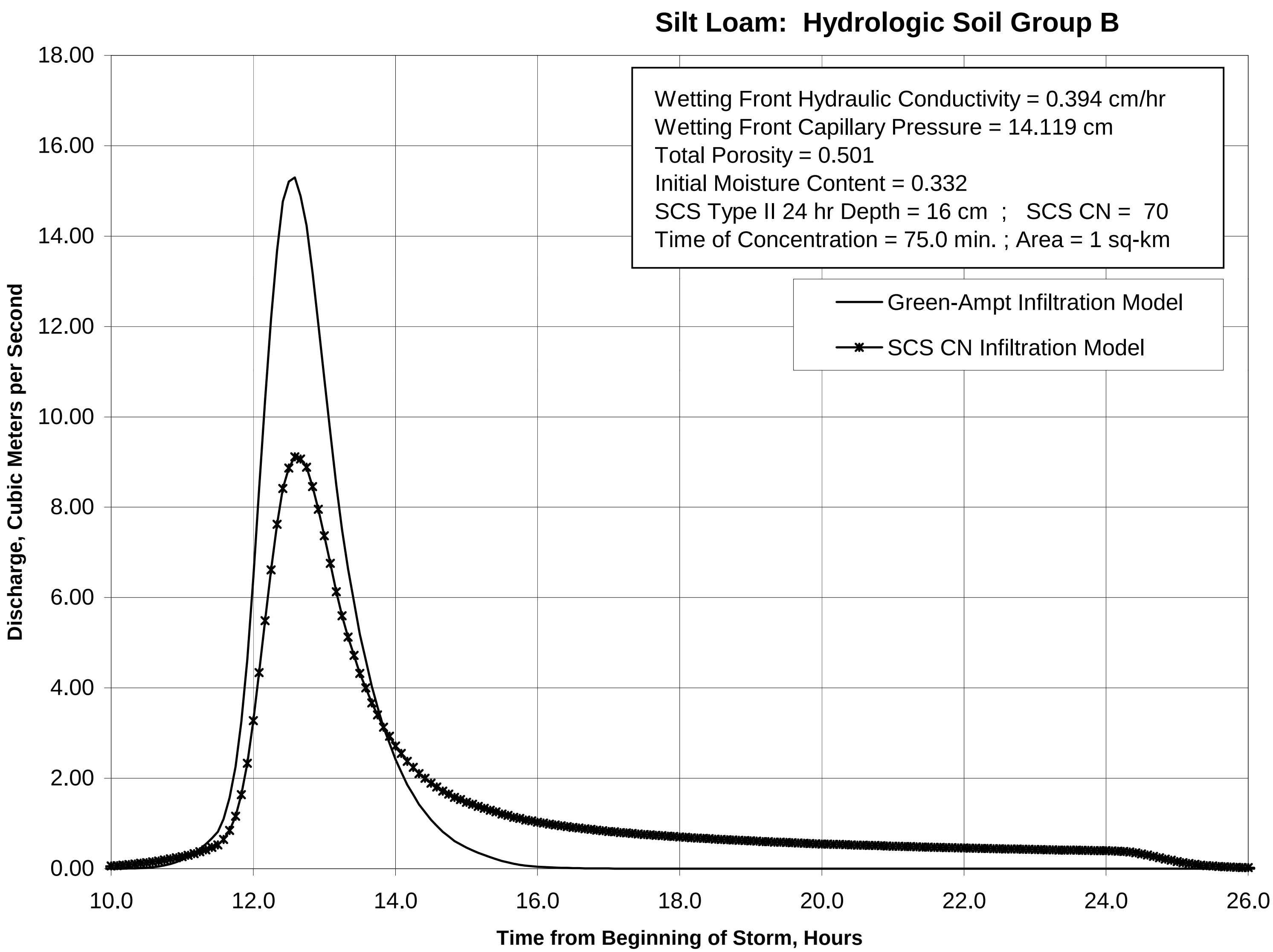

Figure A.17 Equal Volume Runoff Hydrographs, 16 cm Storm Depth, CN = 70, Tc = 75.0 min.

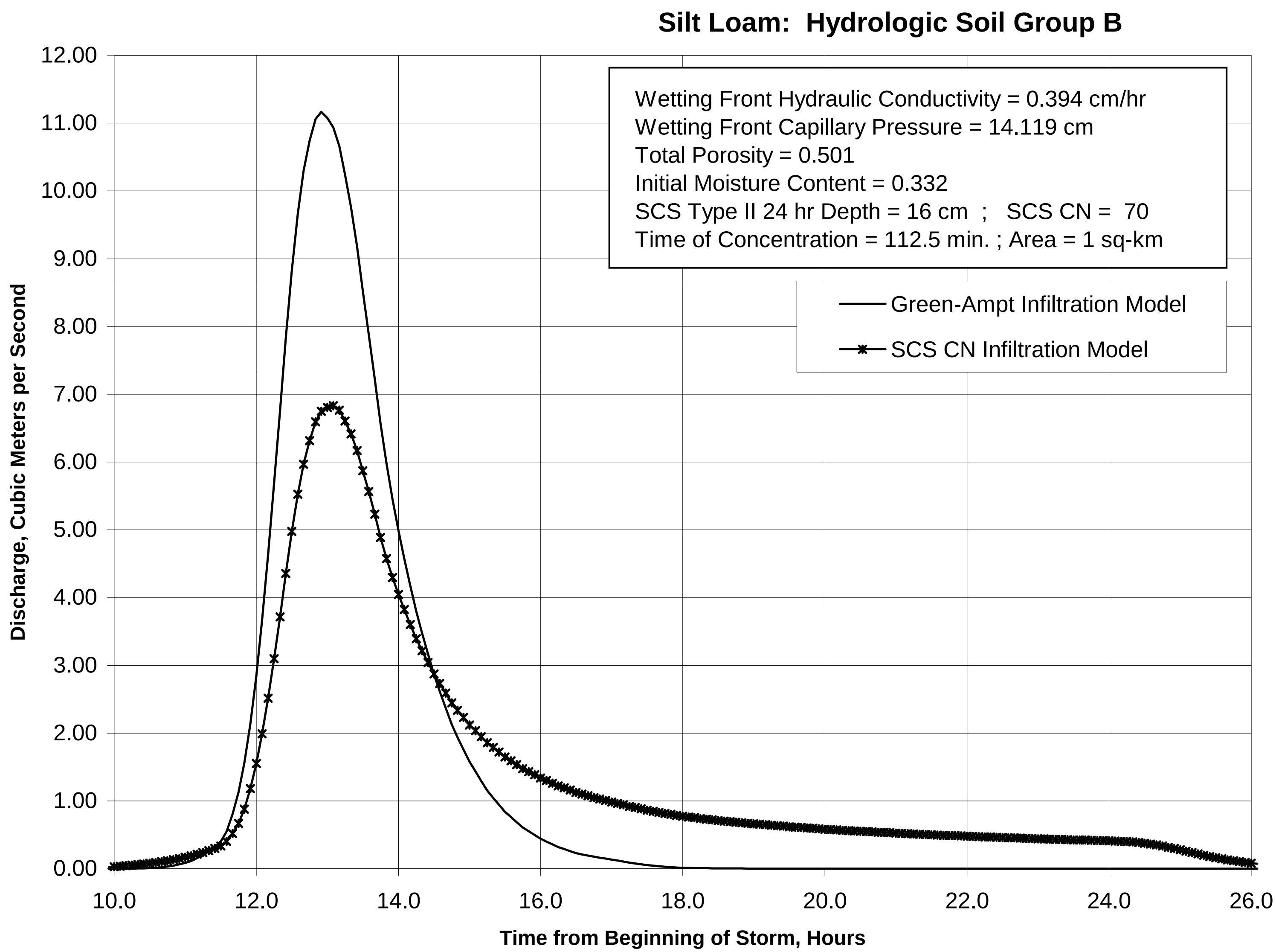

Figure A.18 Equal Volume Runoff Hydrographs, 16 cm Storm Depth, CN = 70, Tc = 112.5 min.

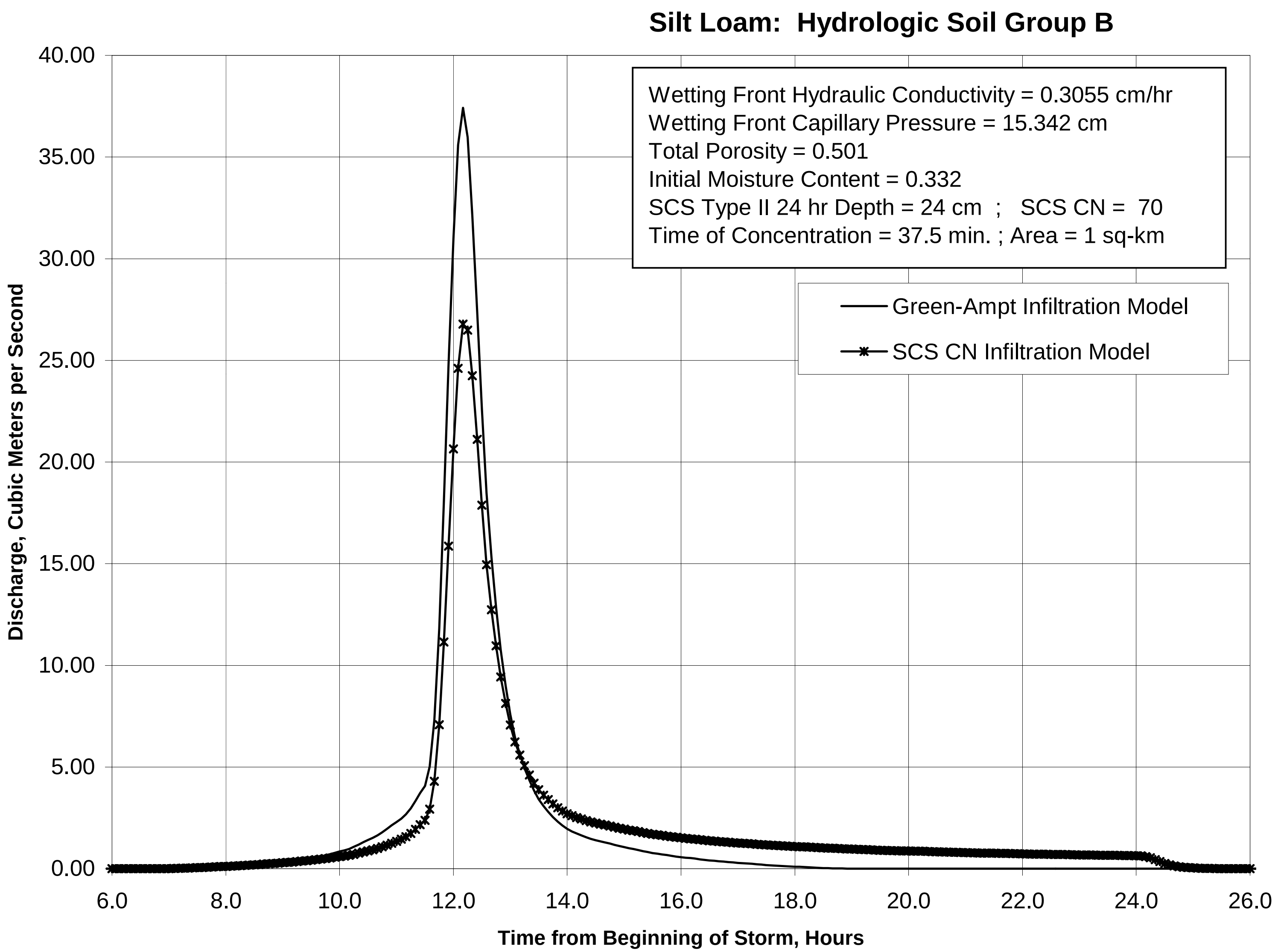

Figure A.19   Equal Volume Runoff Hydrographs, 24 cm Storm Depth, CN = 70, Tc = 37.5 min.

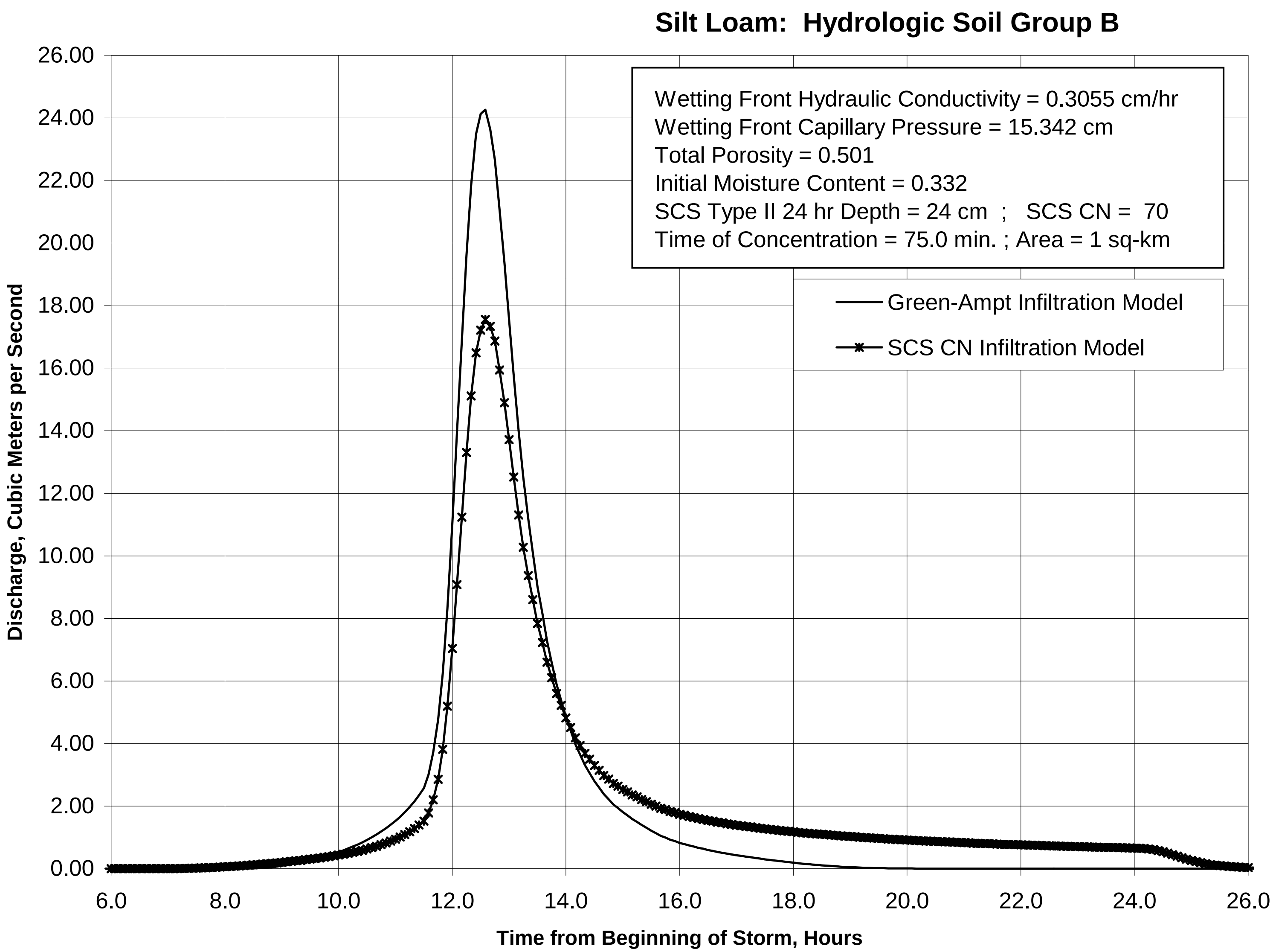

Figure A.20 Equal Volume Runoff Hydrographs, 24 cm Storm Depth, CN = 70, Tc = 75.0 min.

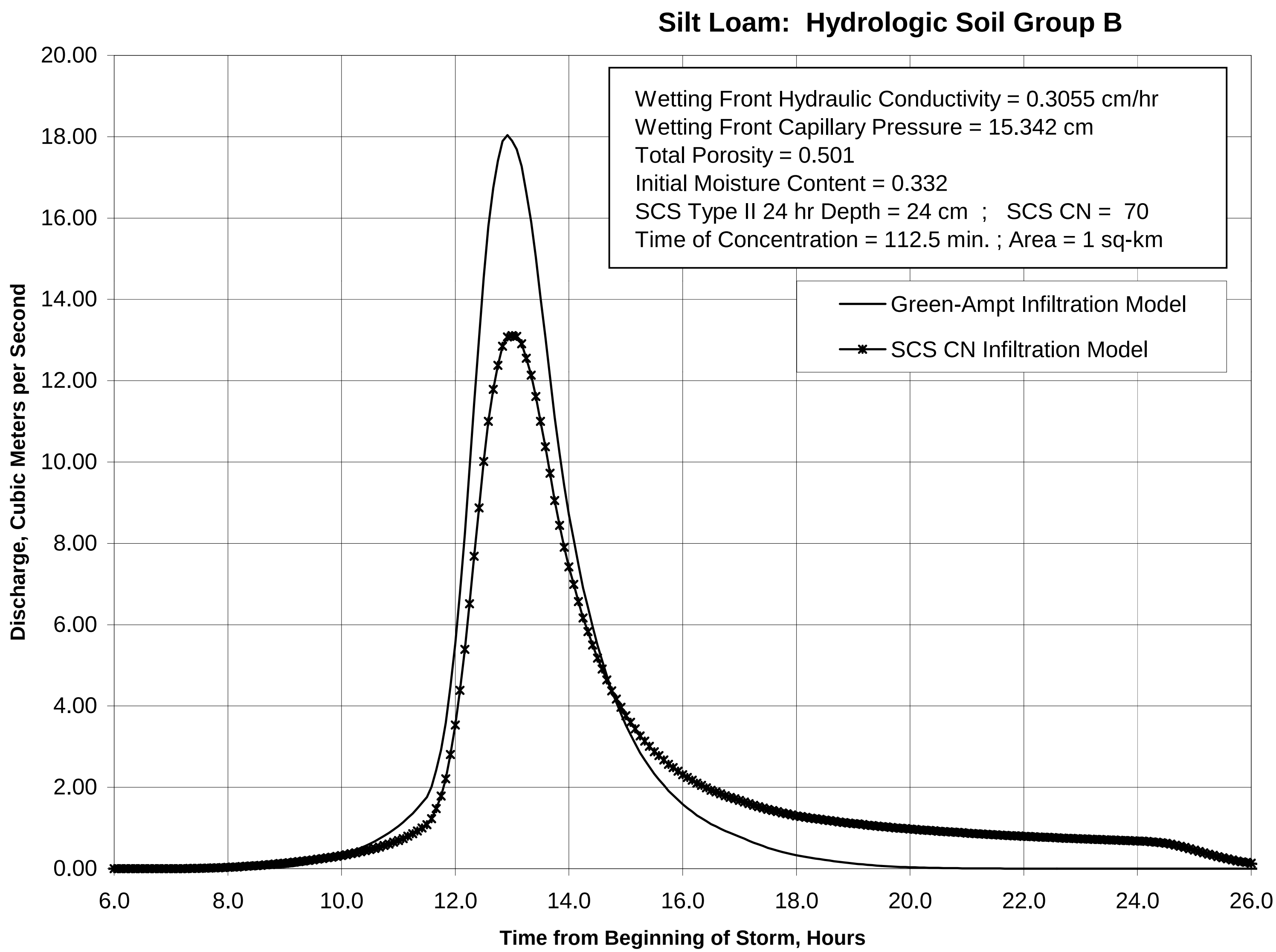

Figure A.21 Equal Volume Runoff Hydrographs, 24 cm Storm Depth, CN = 70, Tc = 112.5 min.

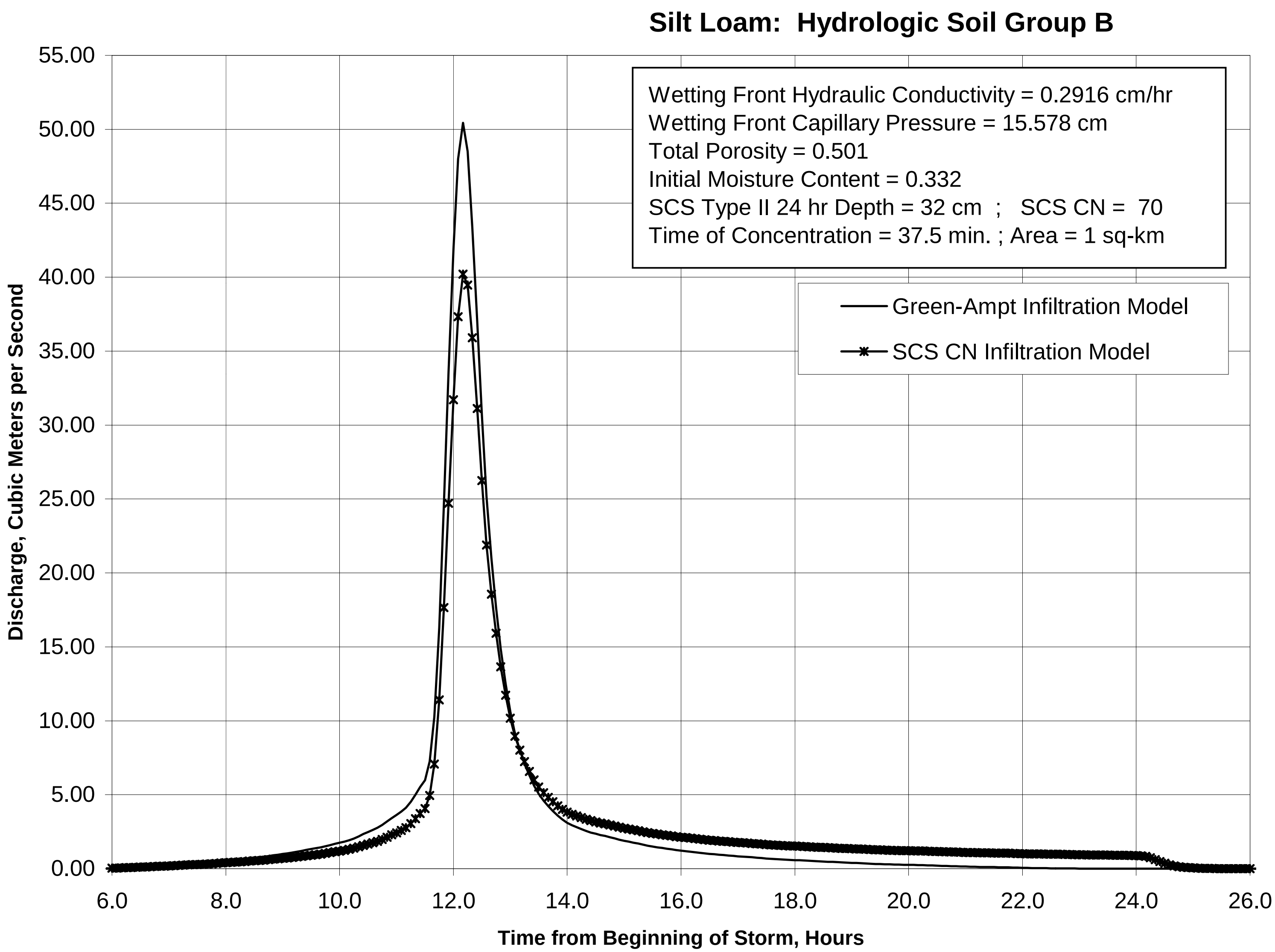

Figure A.22   Equal Volume Runoff Hydrographs, 32 cm Storm Depth, CN = 70, Tc = 37.5 min.

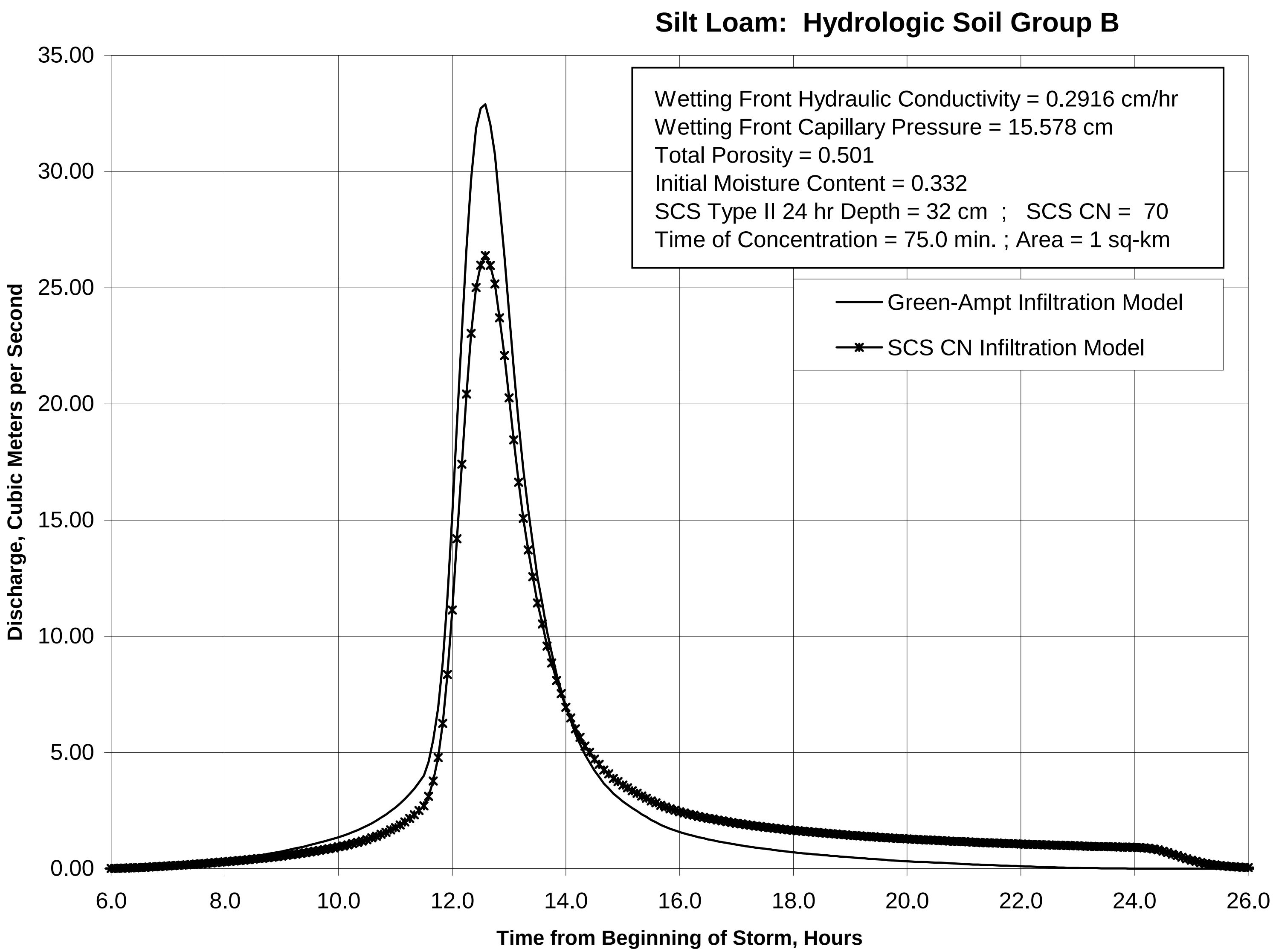

Figure A.23 Equal Volume Runoff Hydrographs, 32 cm Storm Depth, CN = 70, Tc = 75.0 min.

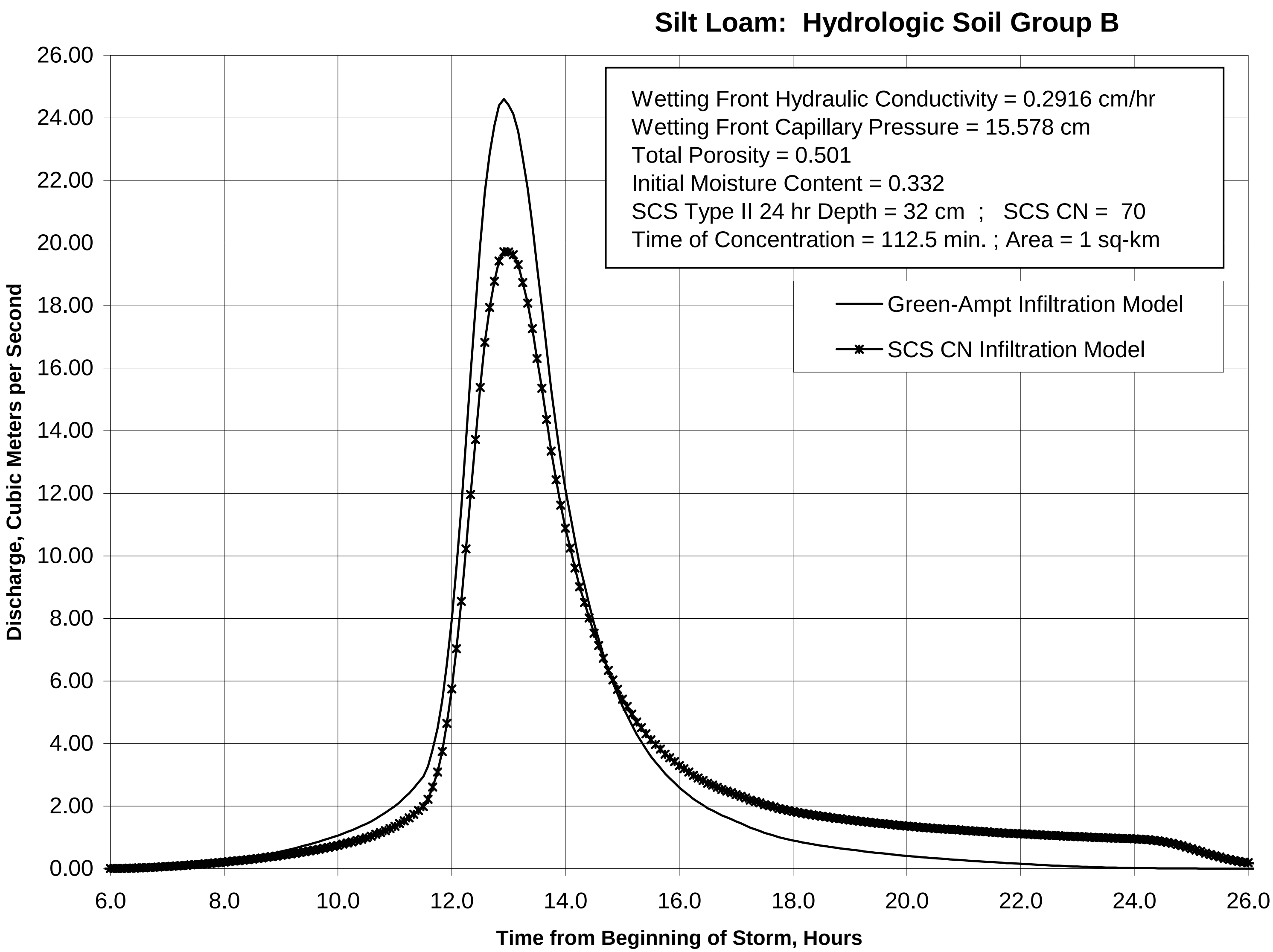

Figure A.24   Equal Volume Runoff Hydrographs, 32 cm Storm Depth, CN = 70, Tc = 112.5 min.

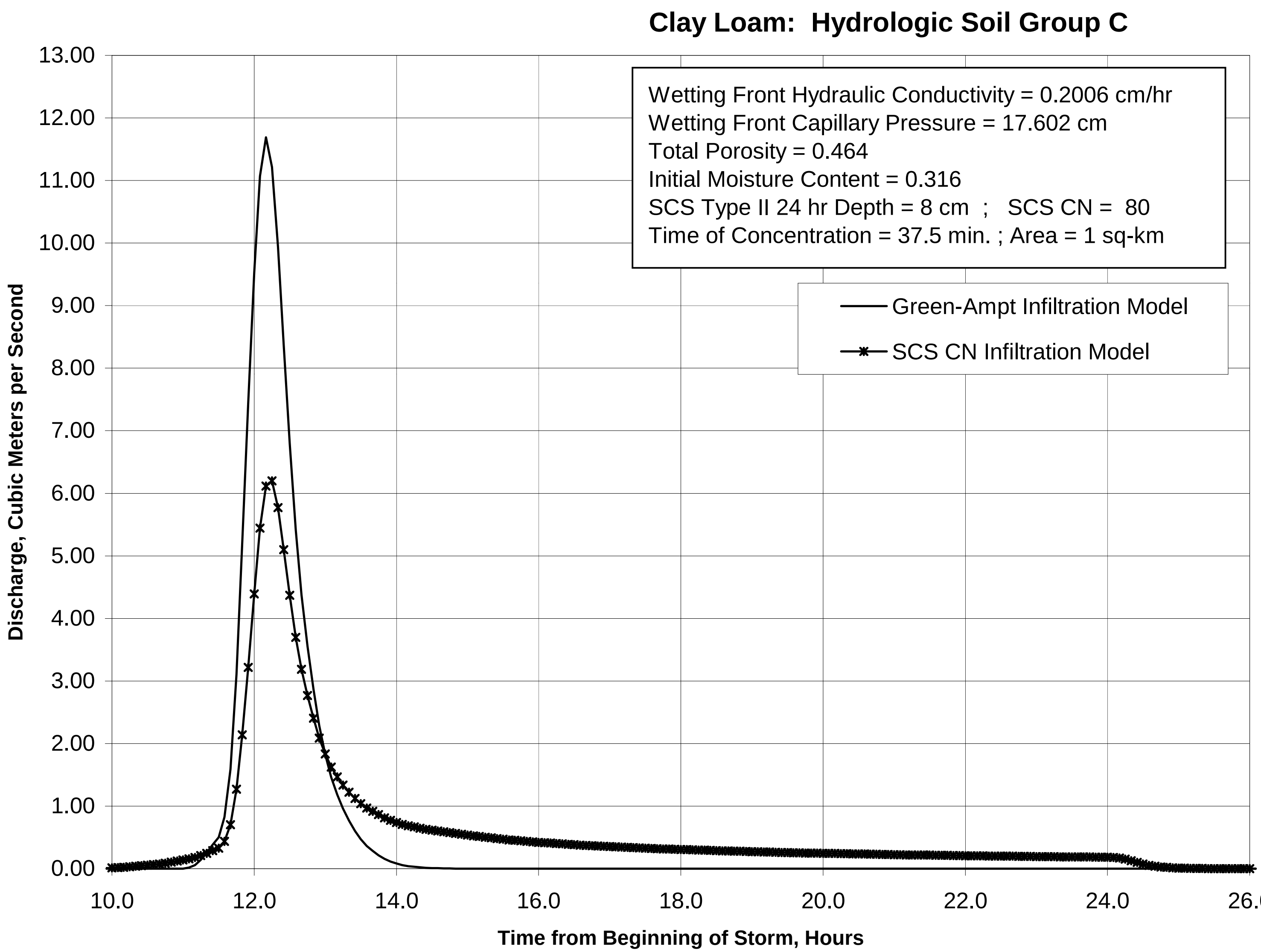

Figure A.25 Equal Volume Runoff Hydrographs, 8 cm Storm Depth, CN = 80, Tc = 37.5 min.

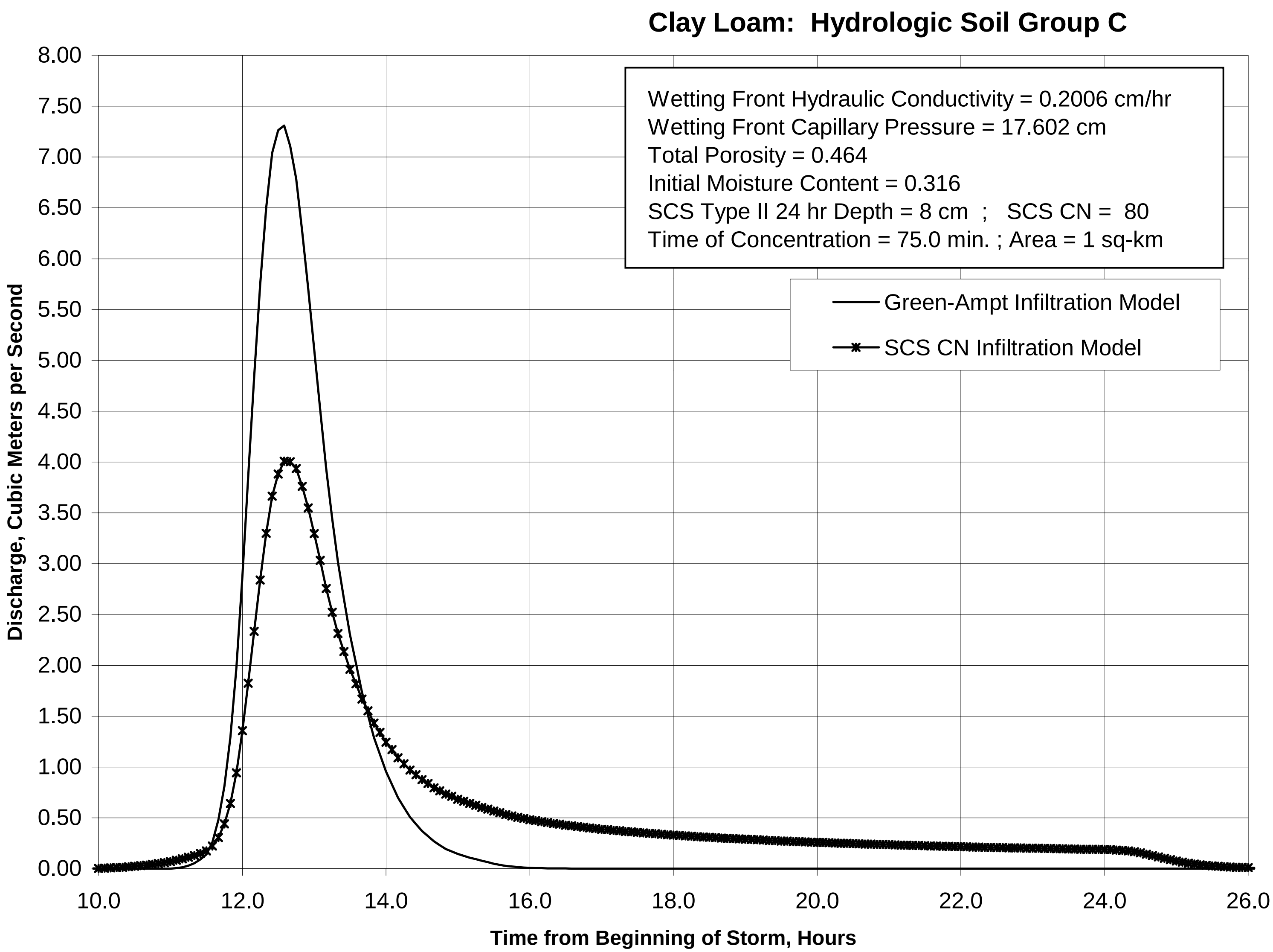

Figure A.26 Equal Volume Runoff Hydrographs, 8 cm Storm Depth, CN = 80, Tc = 75.0 min.

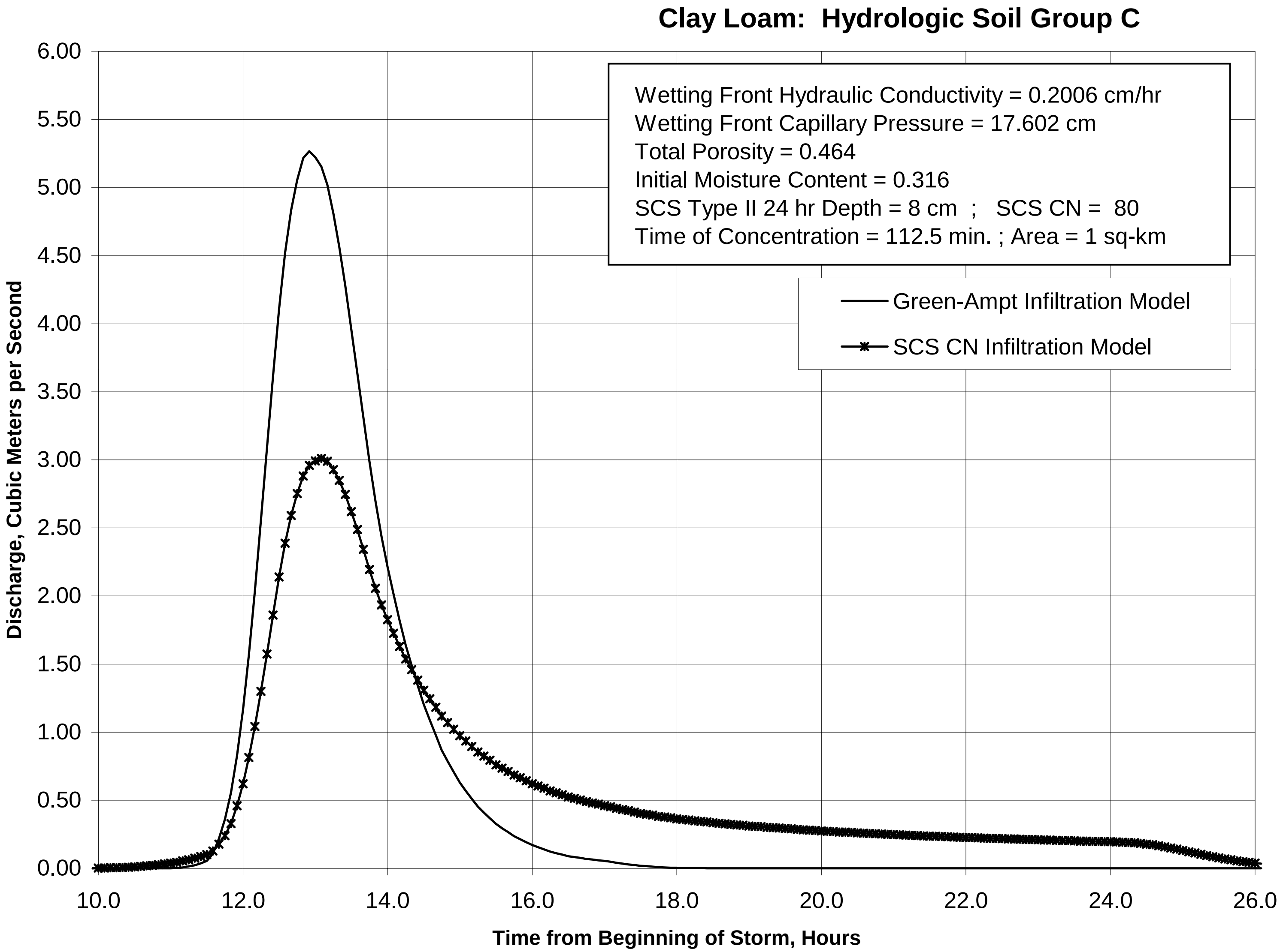

Figure A.27 Equal Volume Runoff Hydrographs, 8 cm Storm Depth, CN = 80, Tc = 112.5 min.

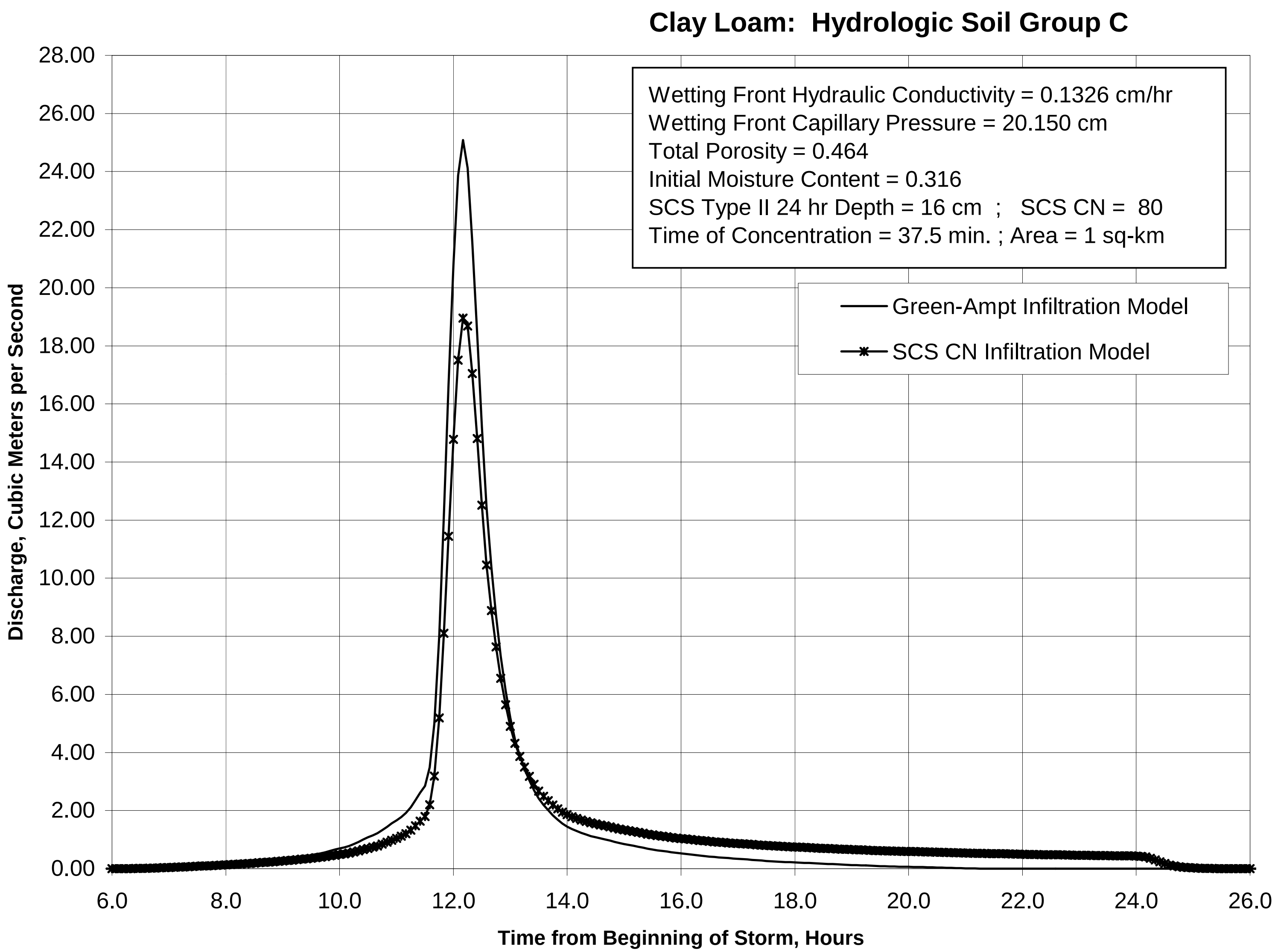

Figure A.28 Equal Volume Runoff Hydrographs, 16 cm Storm Depth, CN = 80, Tc = 37.5 min.

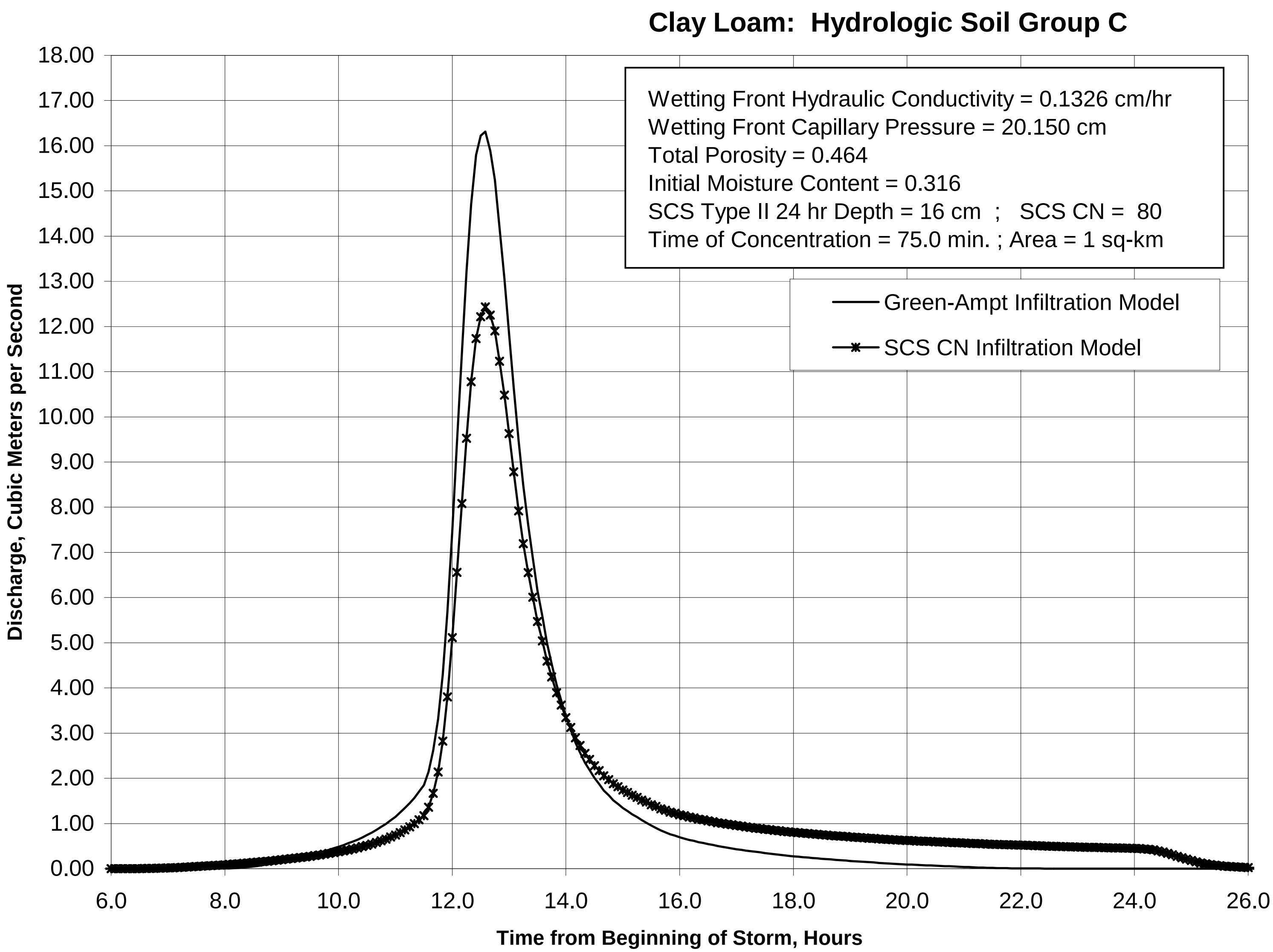

Figure A.29 Equal Volume Runoff Hydrographs, 16 cm Storm Depth, CN = 80, Tc = 75.0 min.

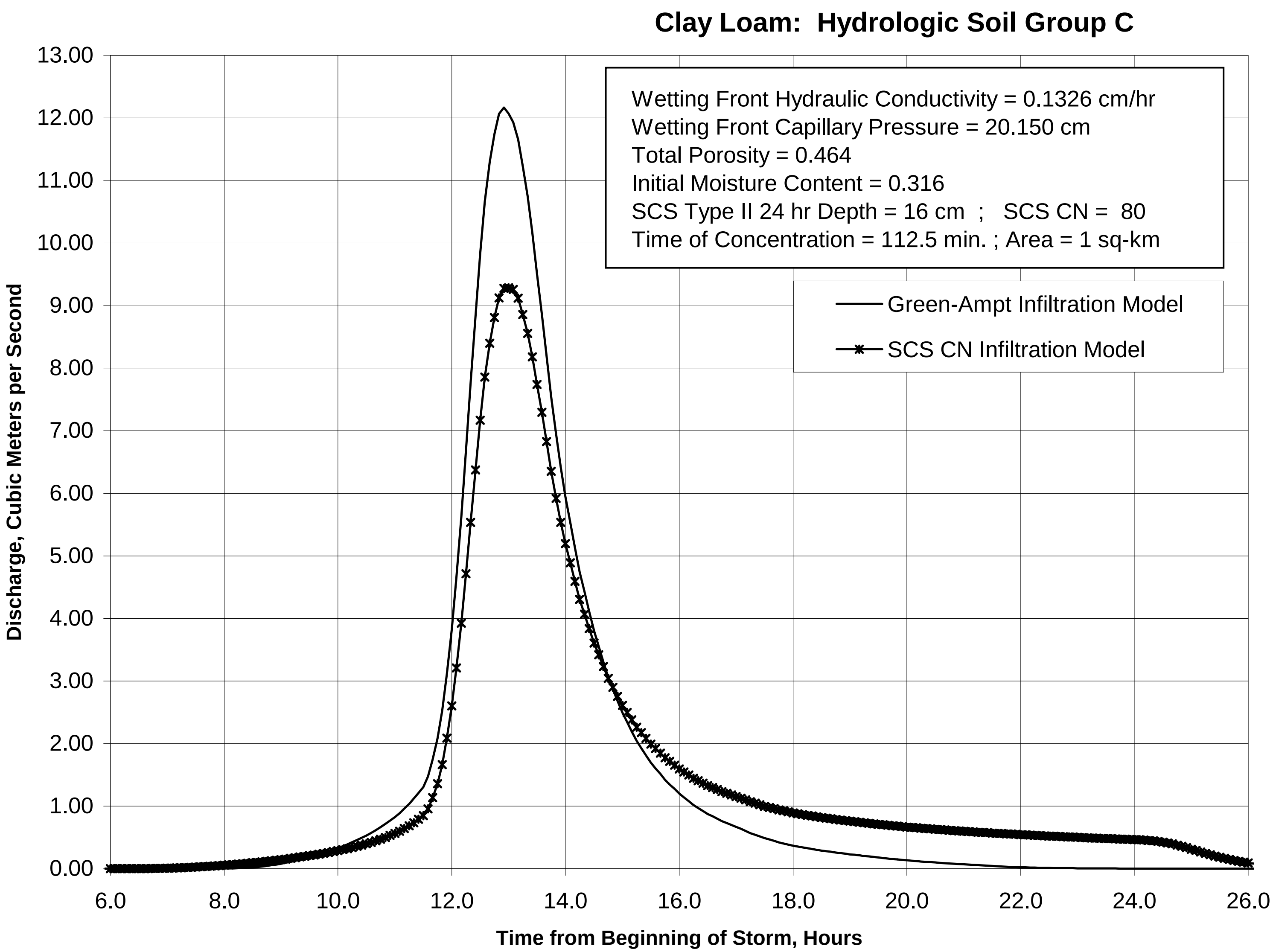

Figure A. 30 Equal Volume Runoff Hydrographs, 16 cm Storm Depth, CN = 80, Tc = 112.5 min.

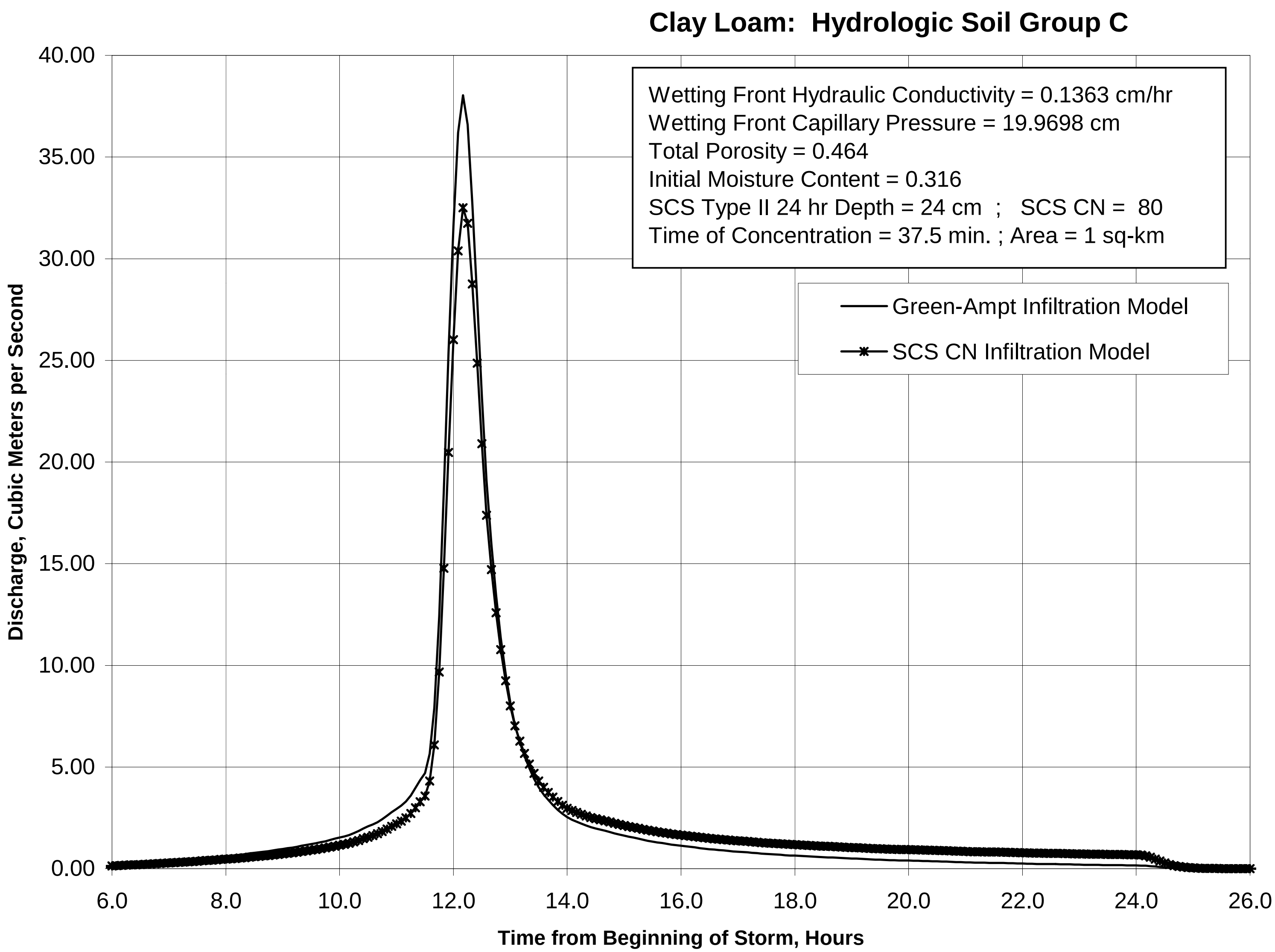

Figure A.31 Equal Volume Runoff Hydrographs, 24 cm Storm Depth, CN = 80, Tc = 37.5 min.

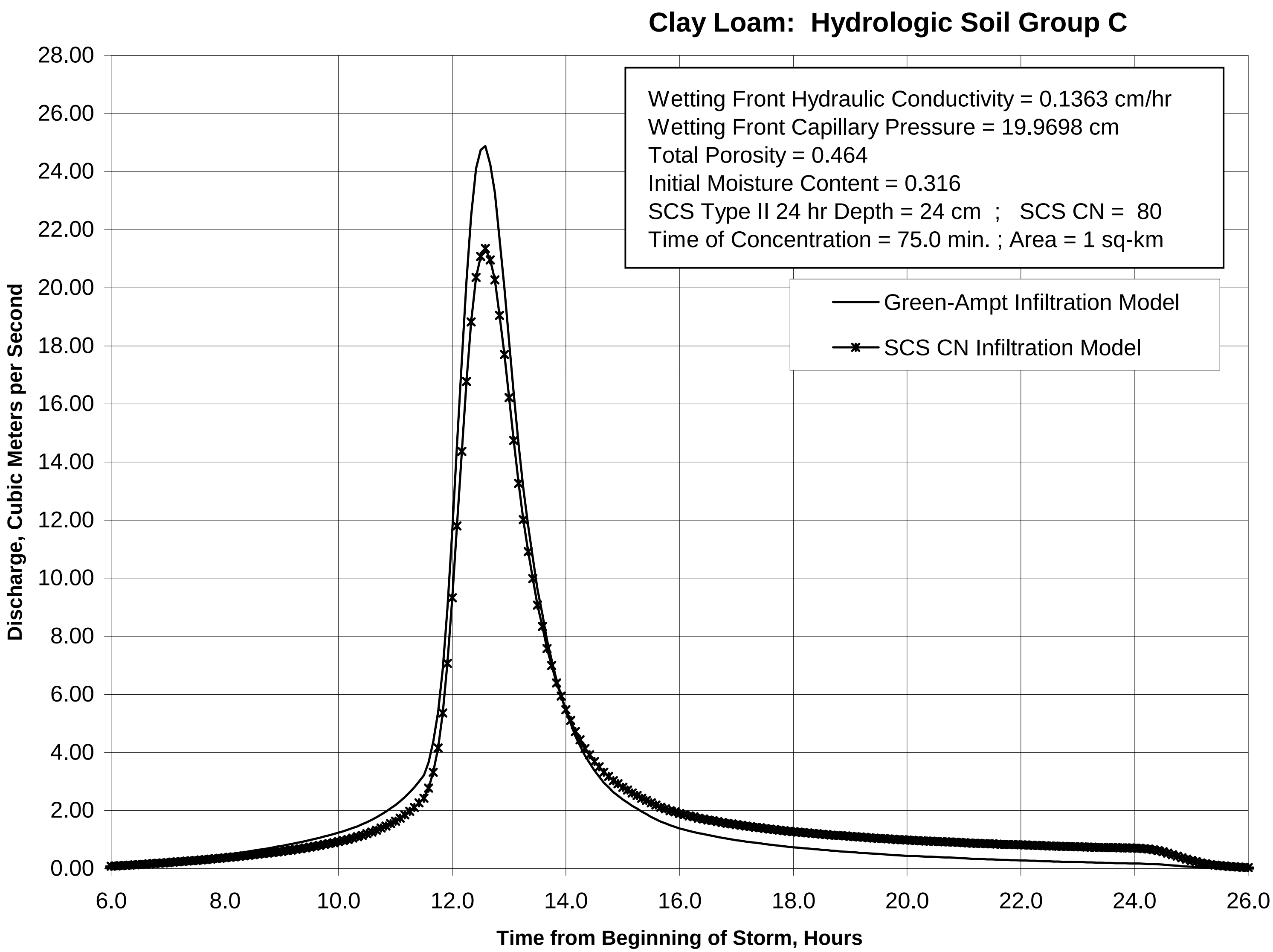

Figure A.32 Equal Volume Runoff Hydrographs, 24 cm Storm Depth, CN = 80, Tc = 75.0 min.

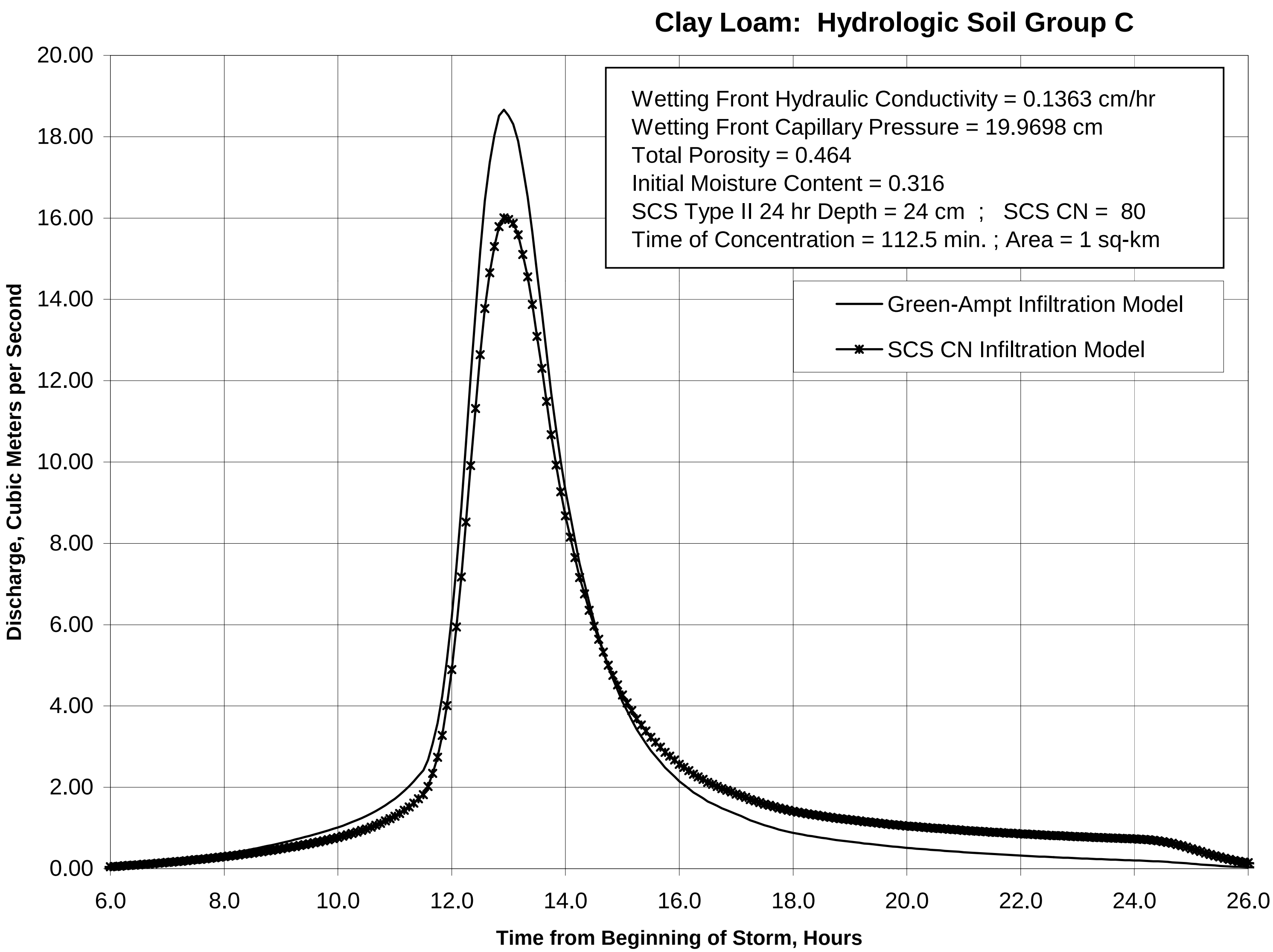

Figure A.33 Equal Volume Runoff Hydrographs, 24 cm Storm Depth, CN = 80, Tc = 112.5 min.

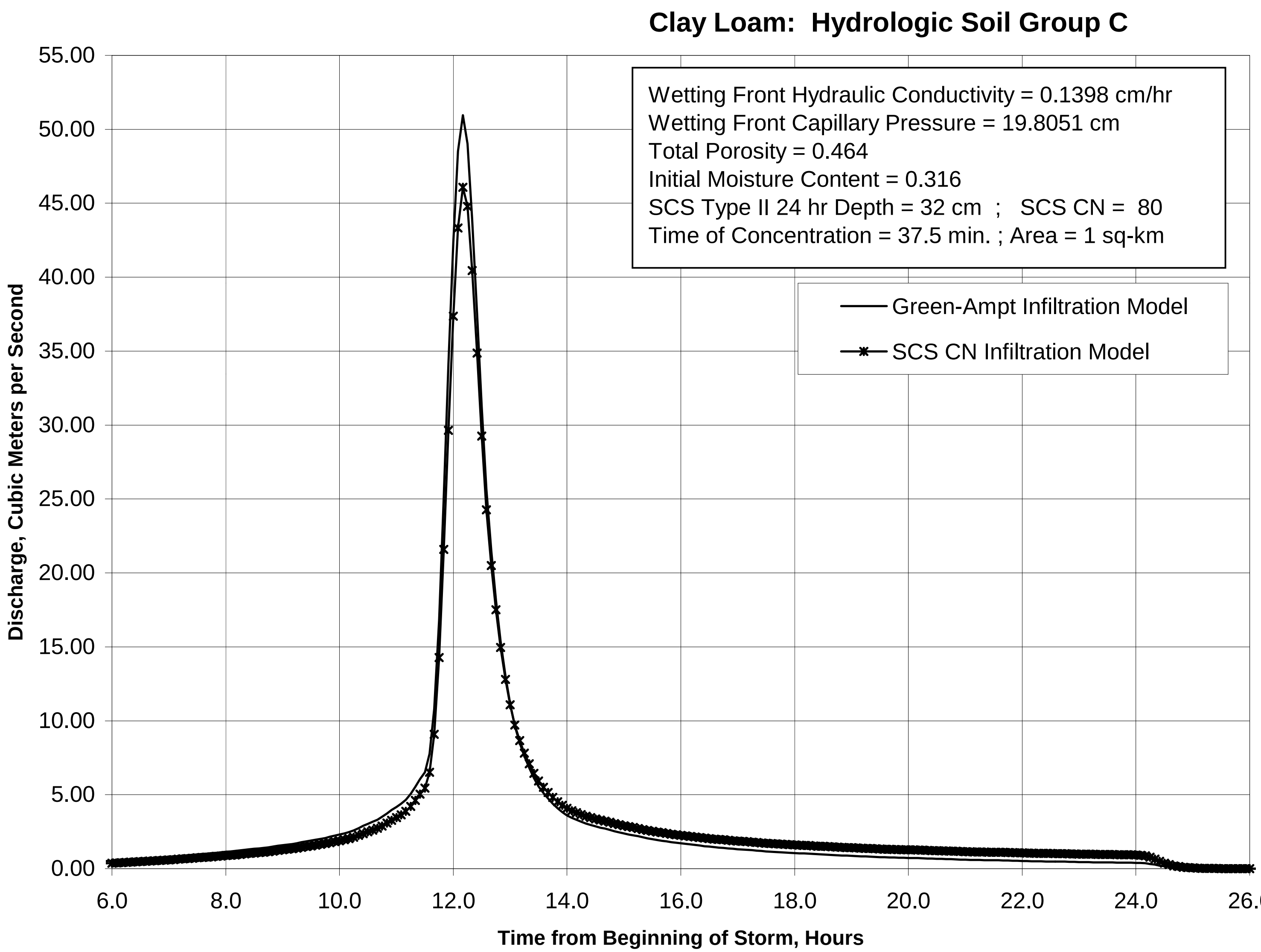

Figure A.34 Equal Volume Runoff Hydrographs, 32 cm Storm Depth, CN = 80, Tc = 37.5 min.

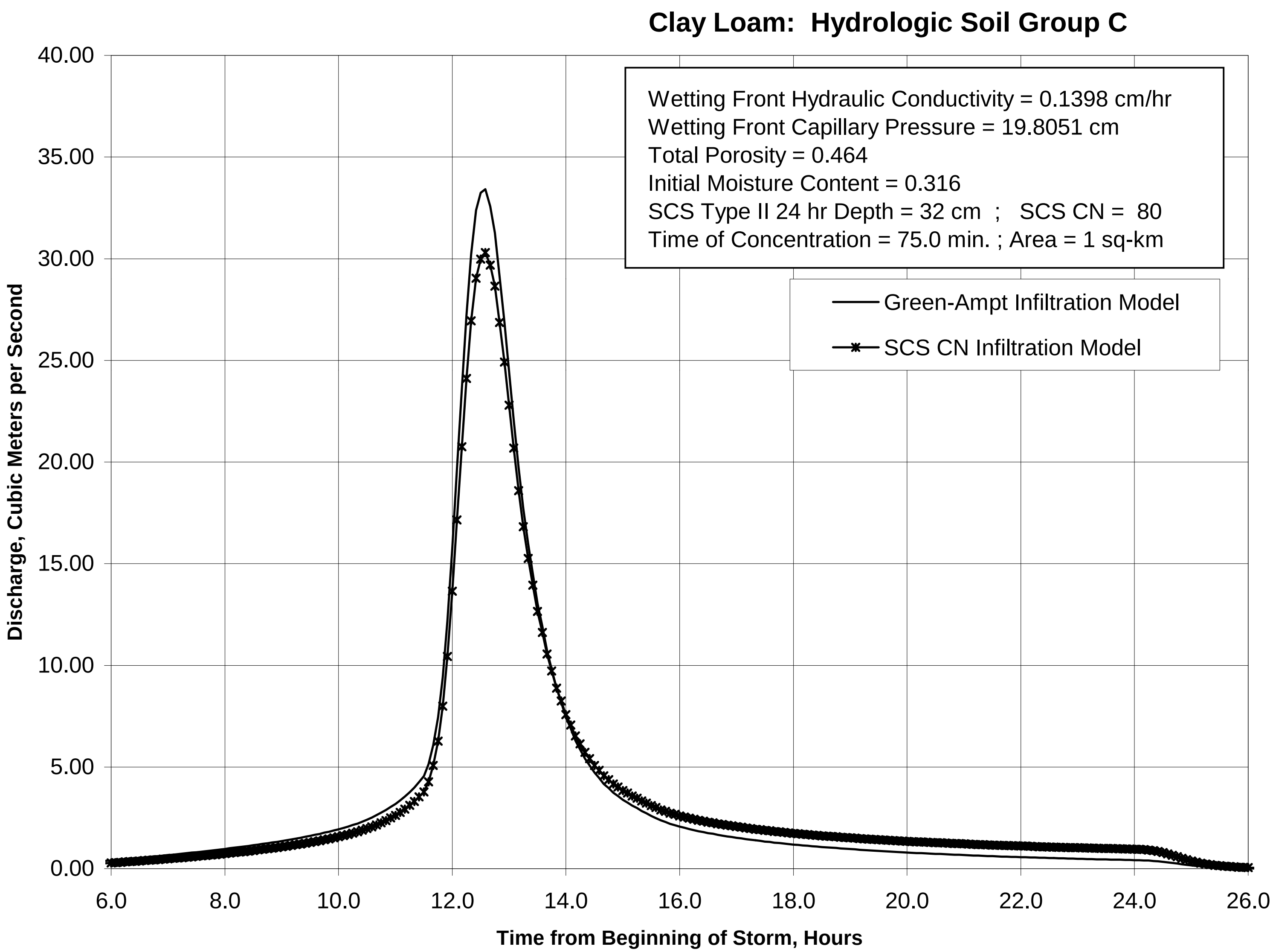

Figure A.35 Equal Volume Runoff Hydrographs, 32 cm Storm Depth, CN = 80, Tc = 75.0 min.

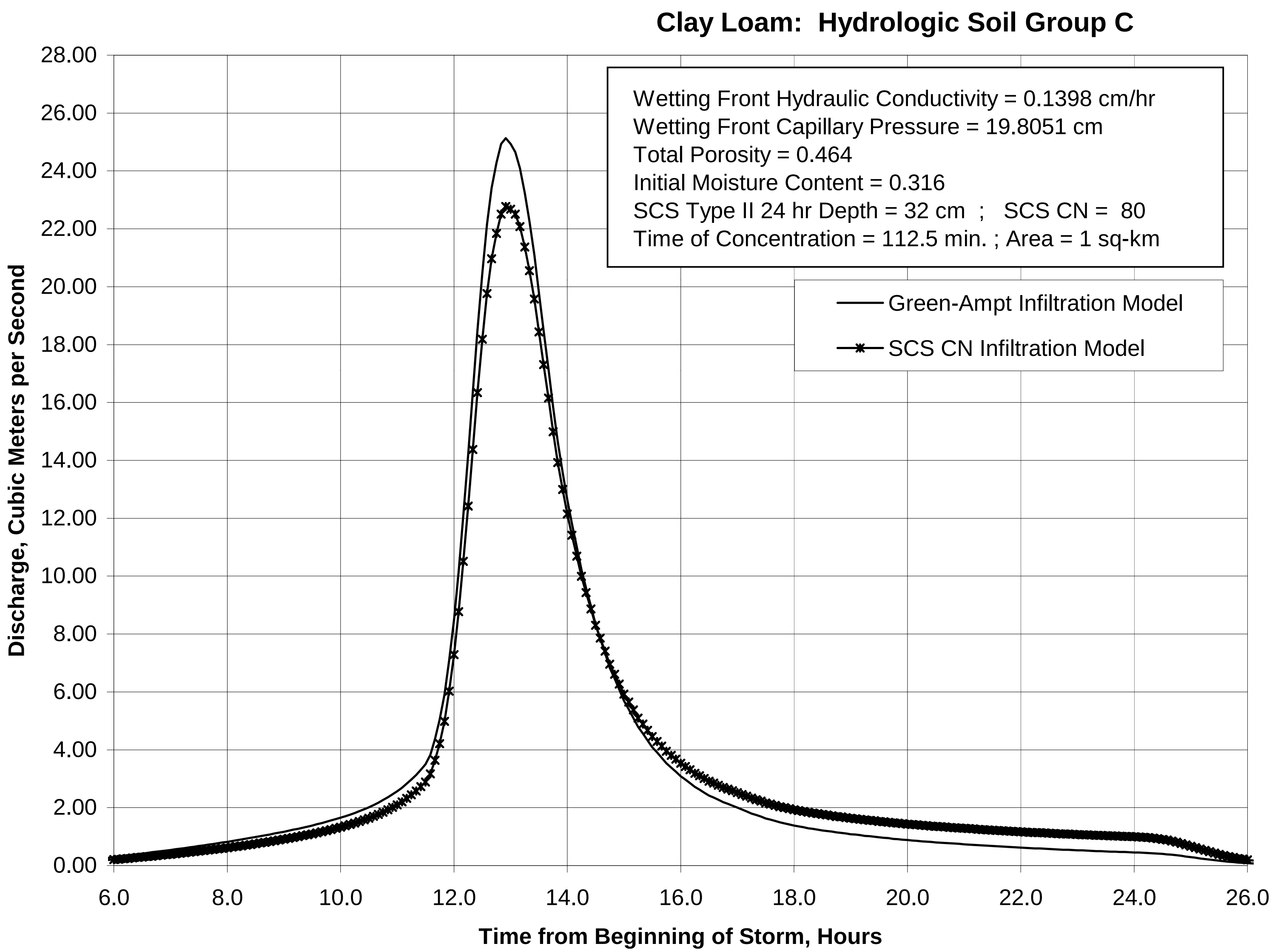

Figure A.36 Equal Volume Runoff Hydrographs, 32 cm Storm Depth, CN = 80, Tc = 112.5 min.

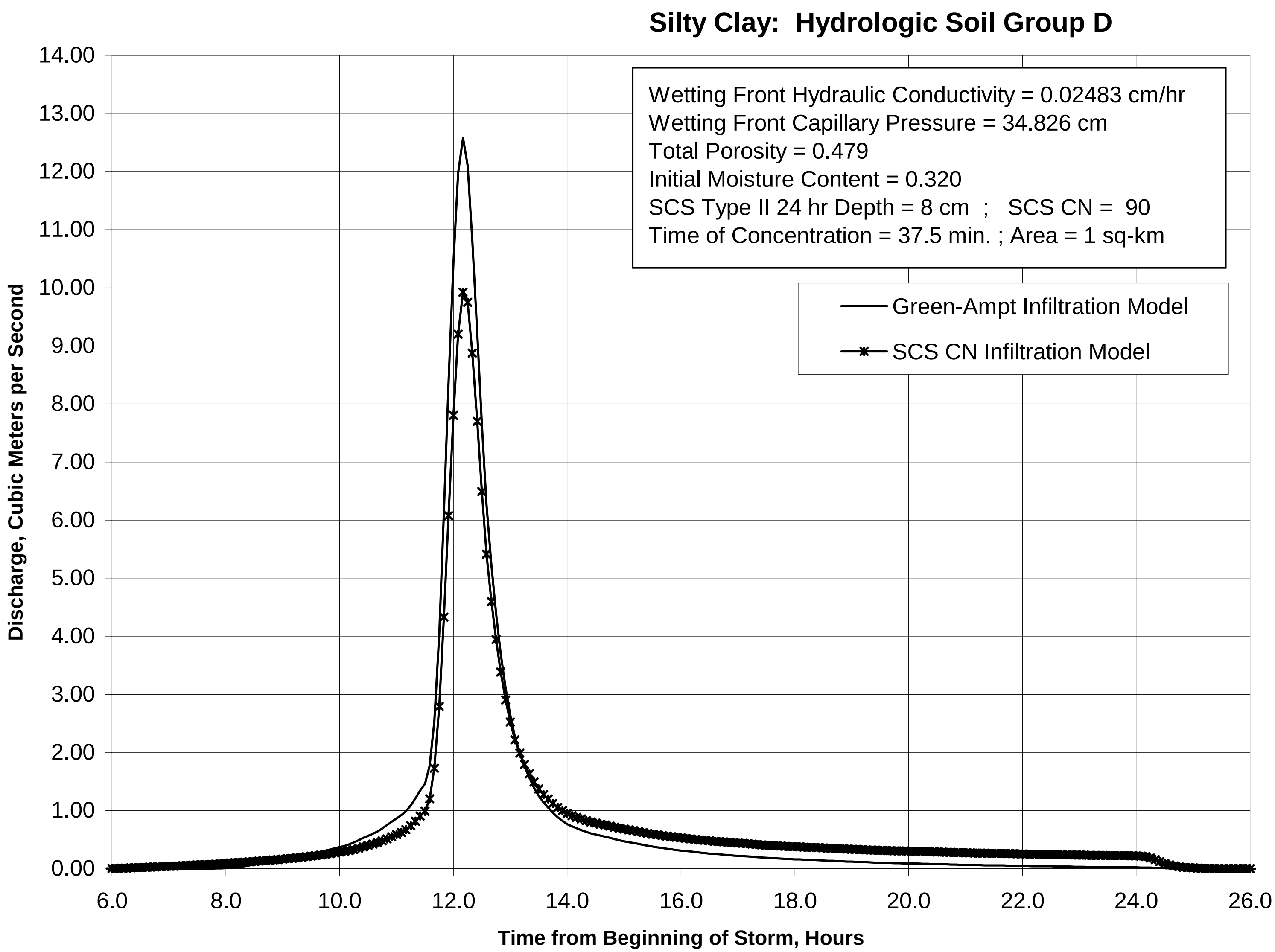

Figure A.37 Equal Volume Runoff Hydrographs, 8 cm Storm Depth, CN = 90, Tc = 37.5 min.

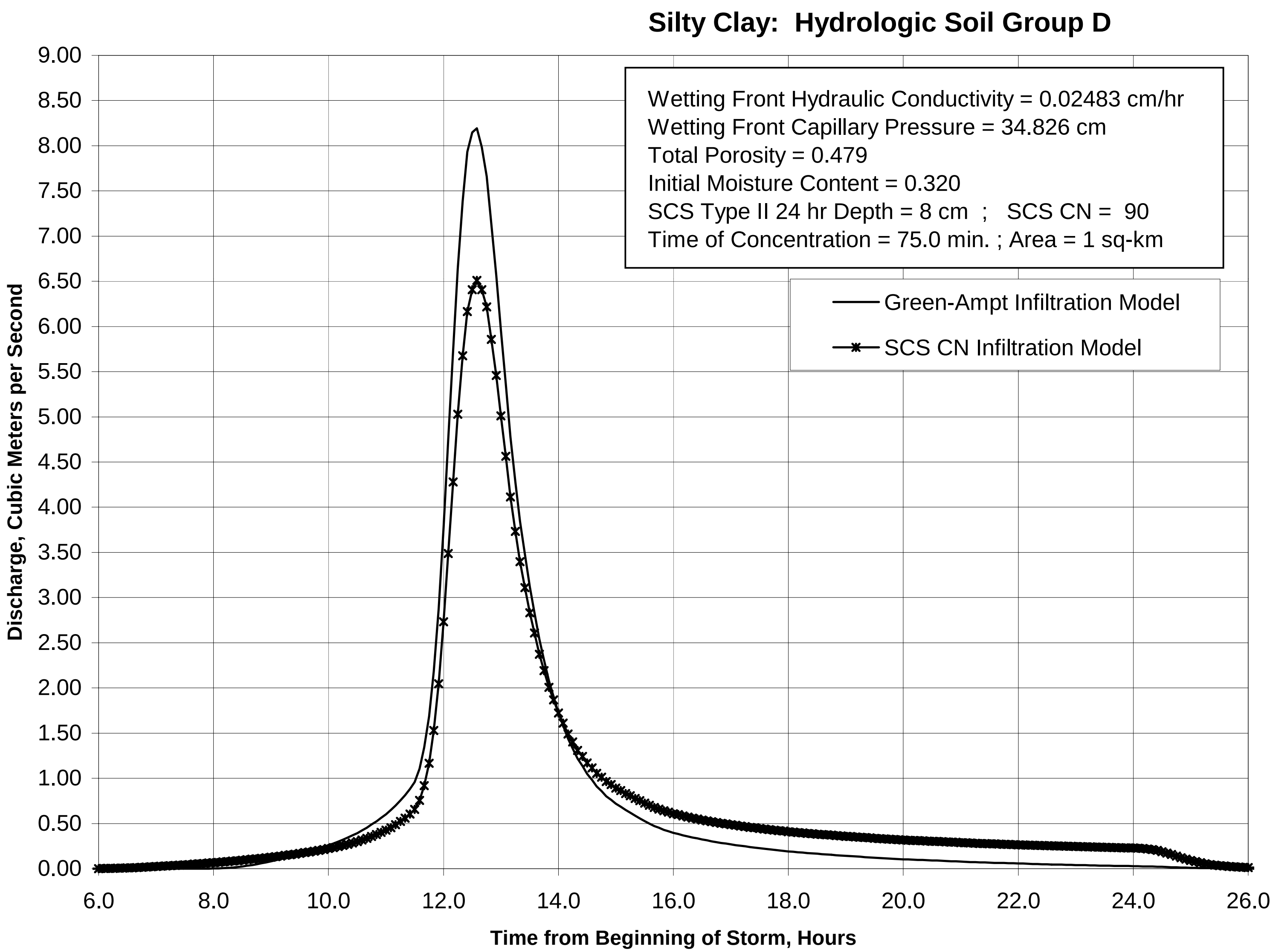

Figure A.38 Equal Volume Runoff Hydrographs, 8 cm Storm Depth, CN = 90, Tc = 75.0 min.

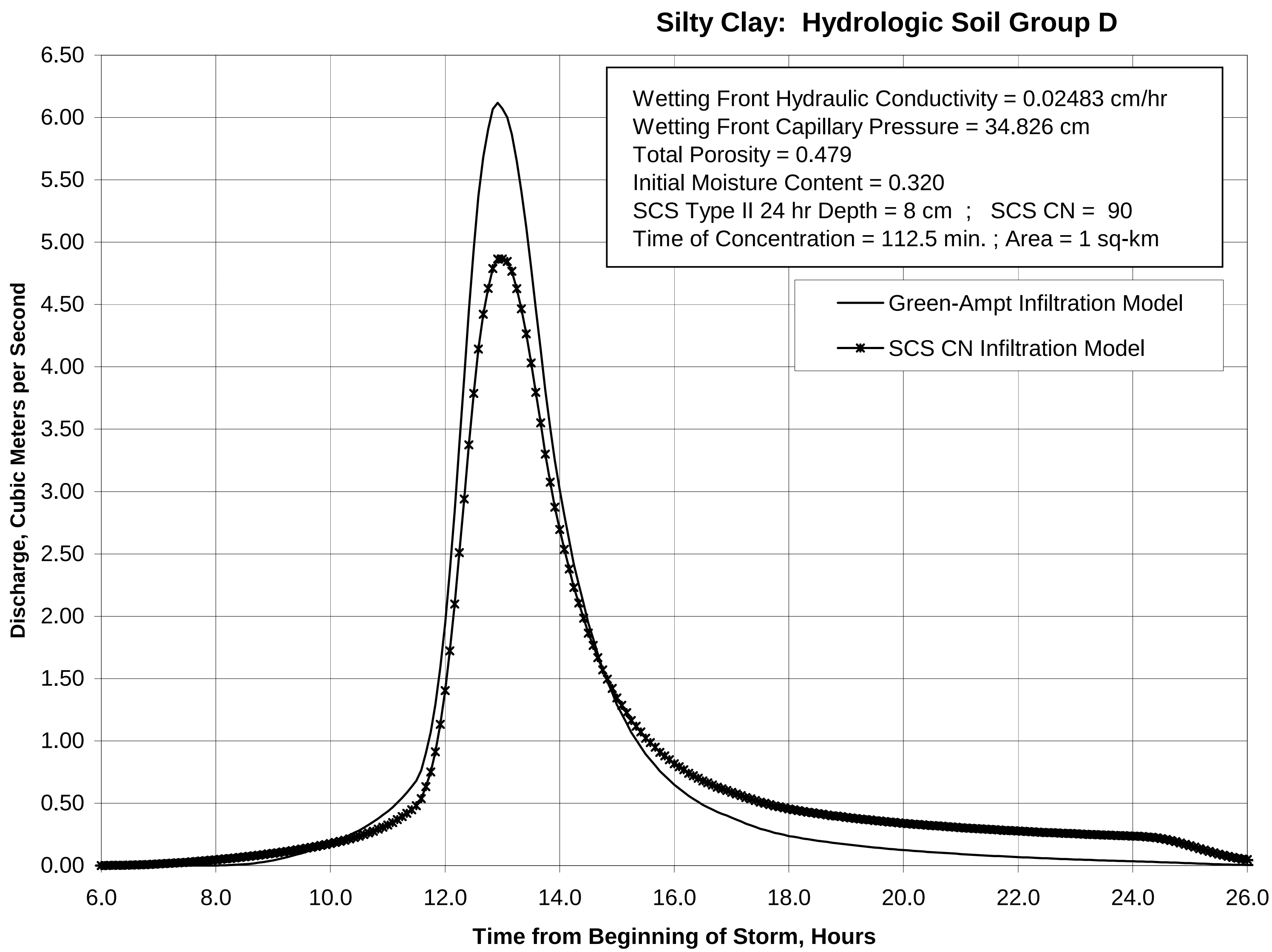

Figure A.39 Equal Volume Runoff Hydrographs, 8 cm Storm Depth, CN = 90, Tc = 112.5 min.

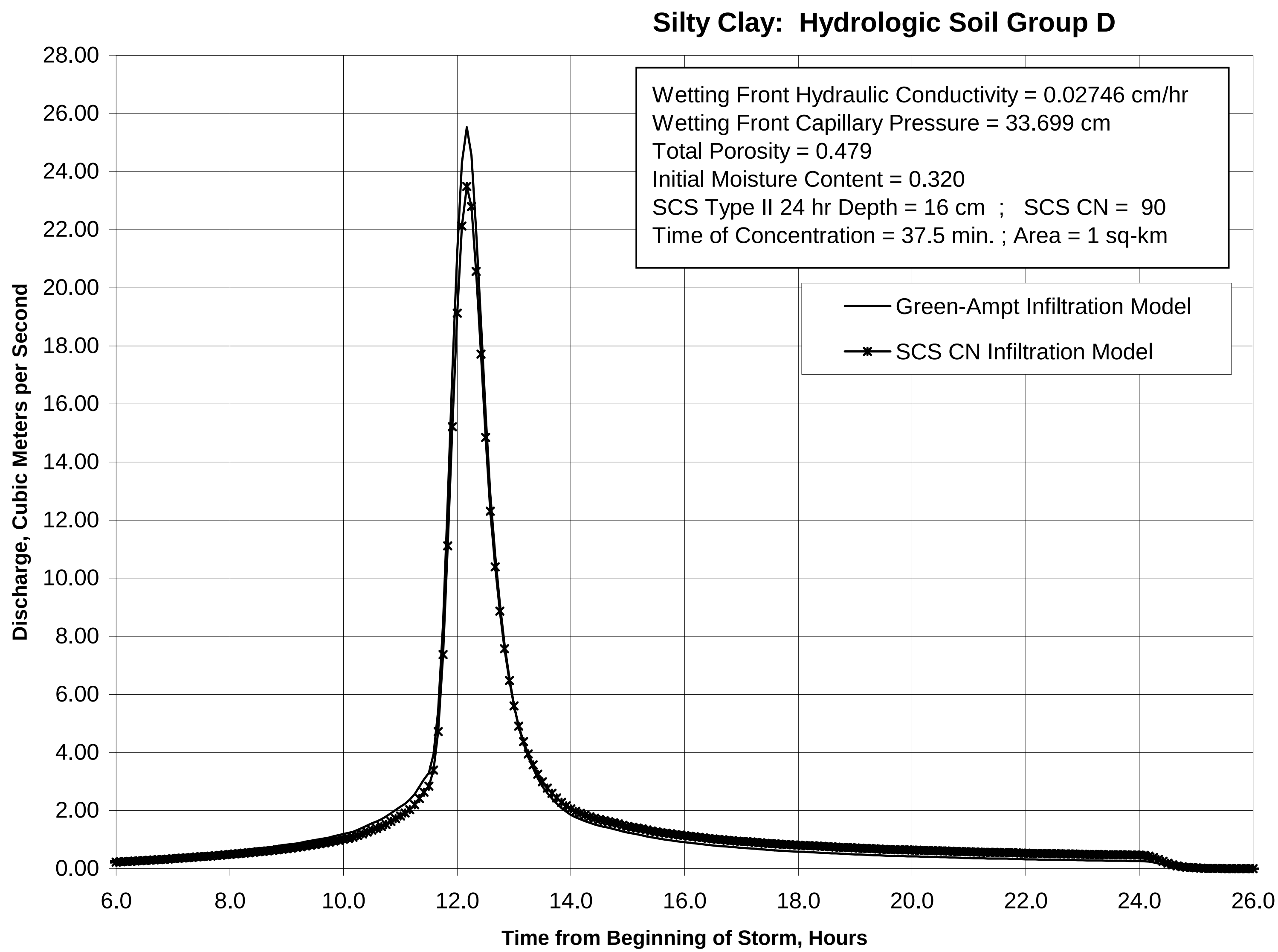

Figure A.40 Equal Volume Runoff Hydrographs, 16 cm Storm Depth, CN = 90, Tc = 37.5 min.

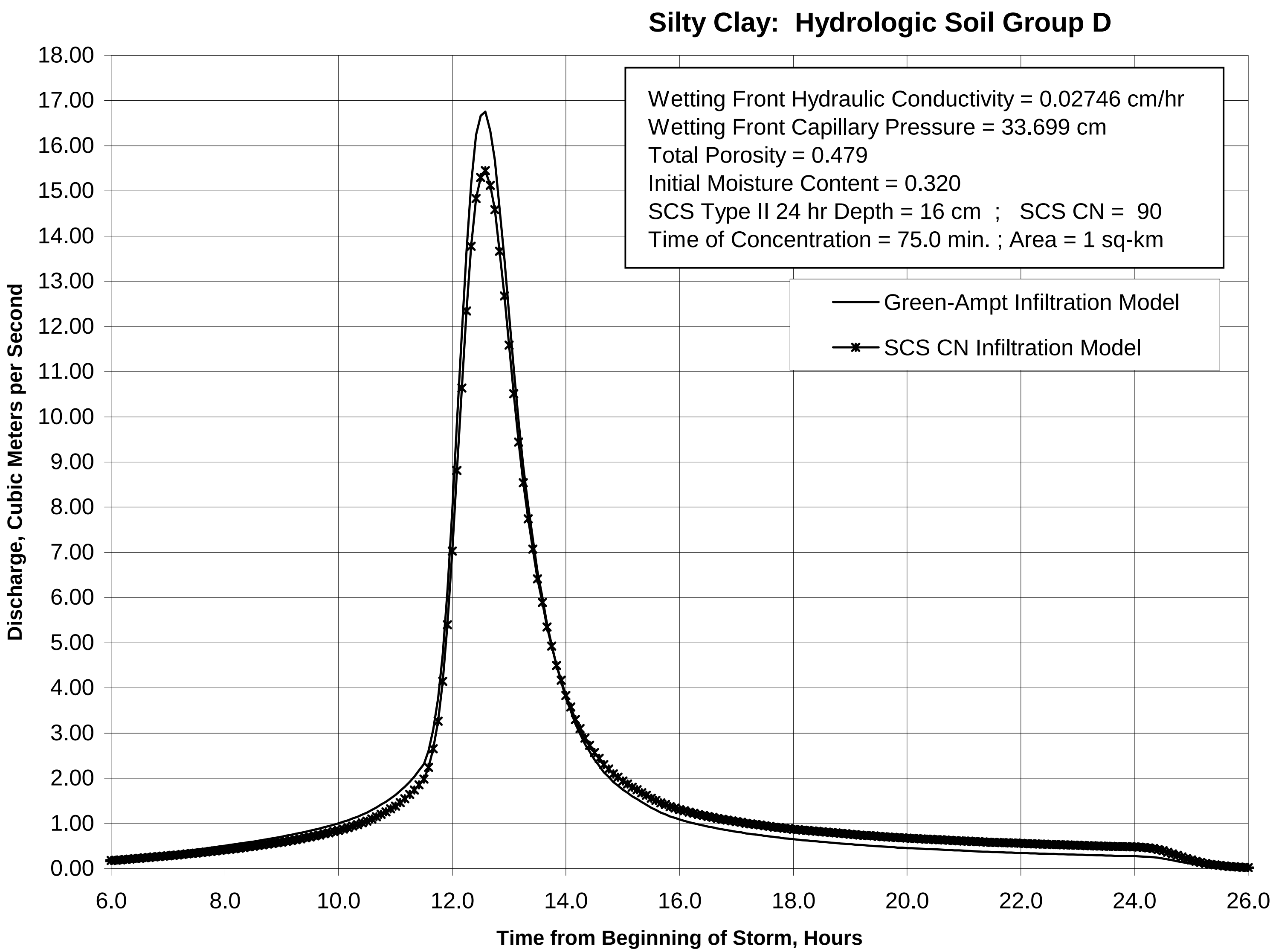

Figure A.41 Equal Volume Runoff Hydrographs, 16 cm Storm Depth, CN = 90, Tc = 75.0 min.

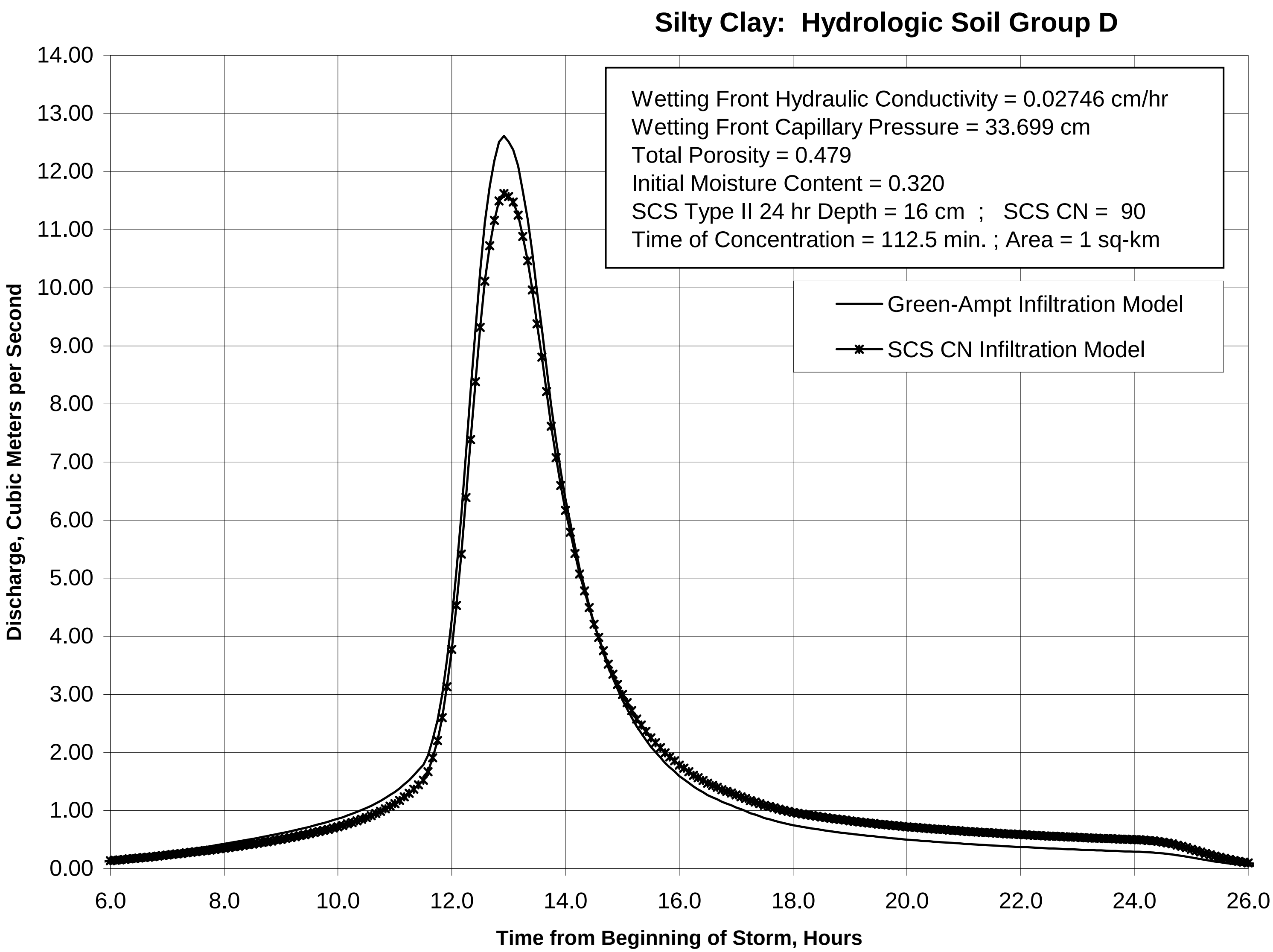

Figure A.42 Equal Volume Runoff Hydrographs, 16 cm Storm Depth, CN = 90, Tc = 112.5 min.

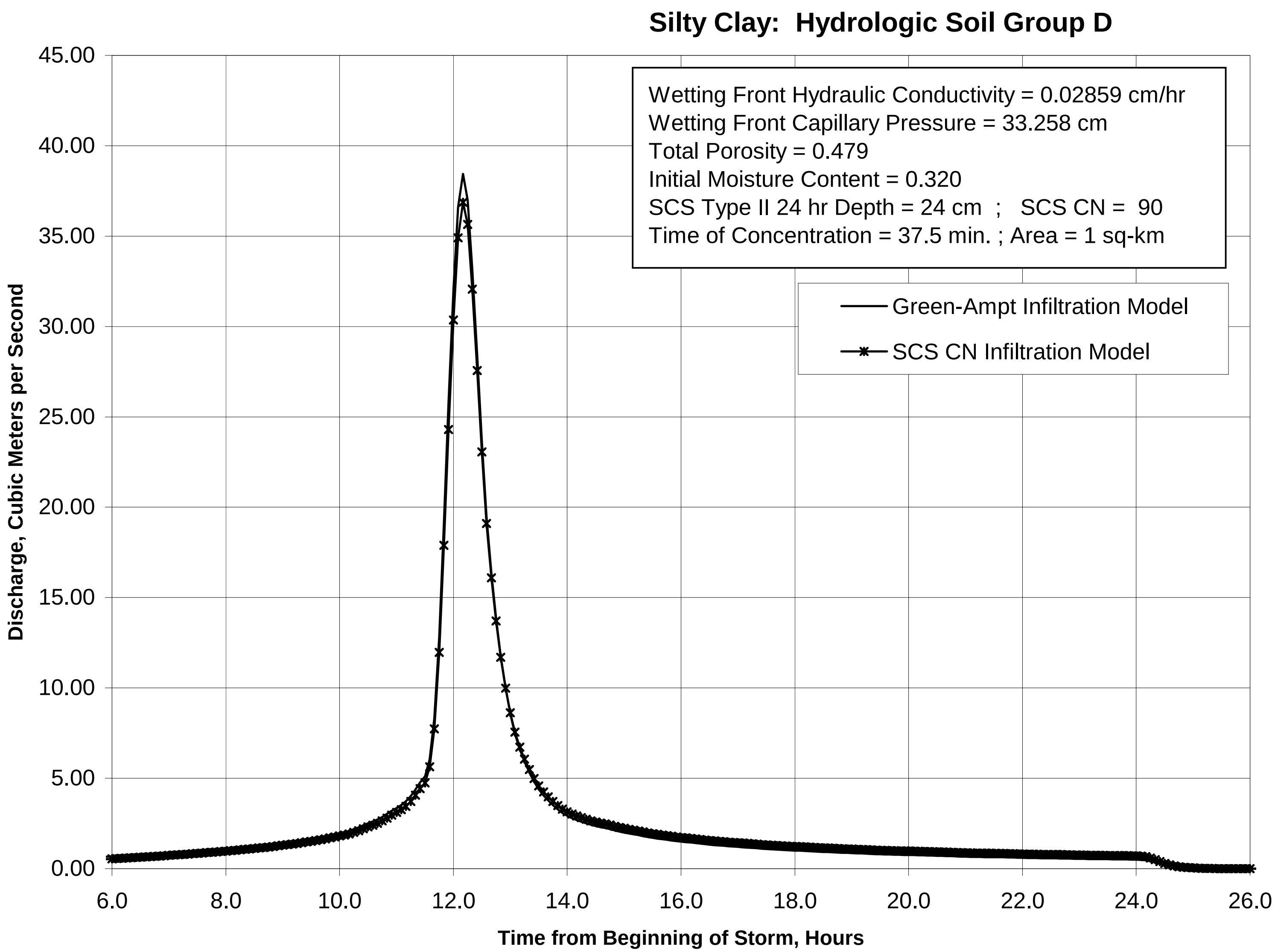

Figure A.43 Equal Volume Runoff Hydrographs, 24 cm Storm Depth, CN = 90, Tc = 37.5 min.

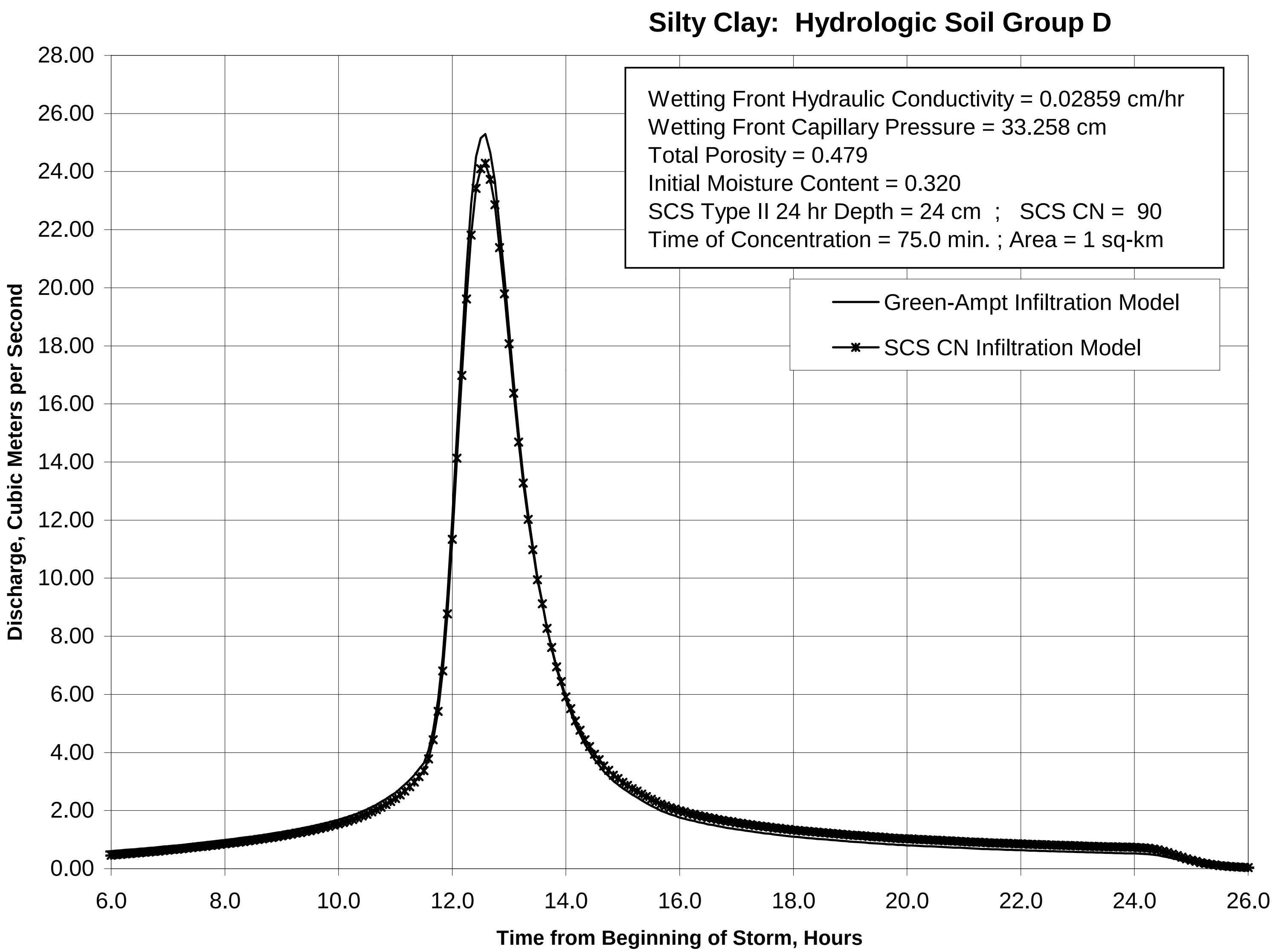

Figure A.44 Equal Volume Runoff Hydrographs, 24 cm Storm Depth, CN = 90, Tc = 75.0 min.

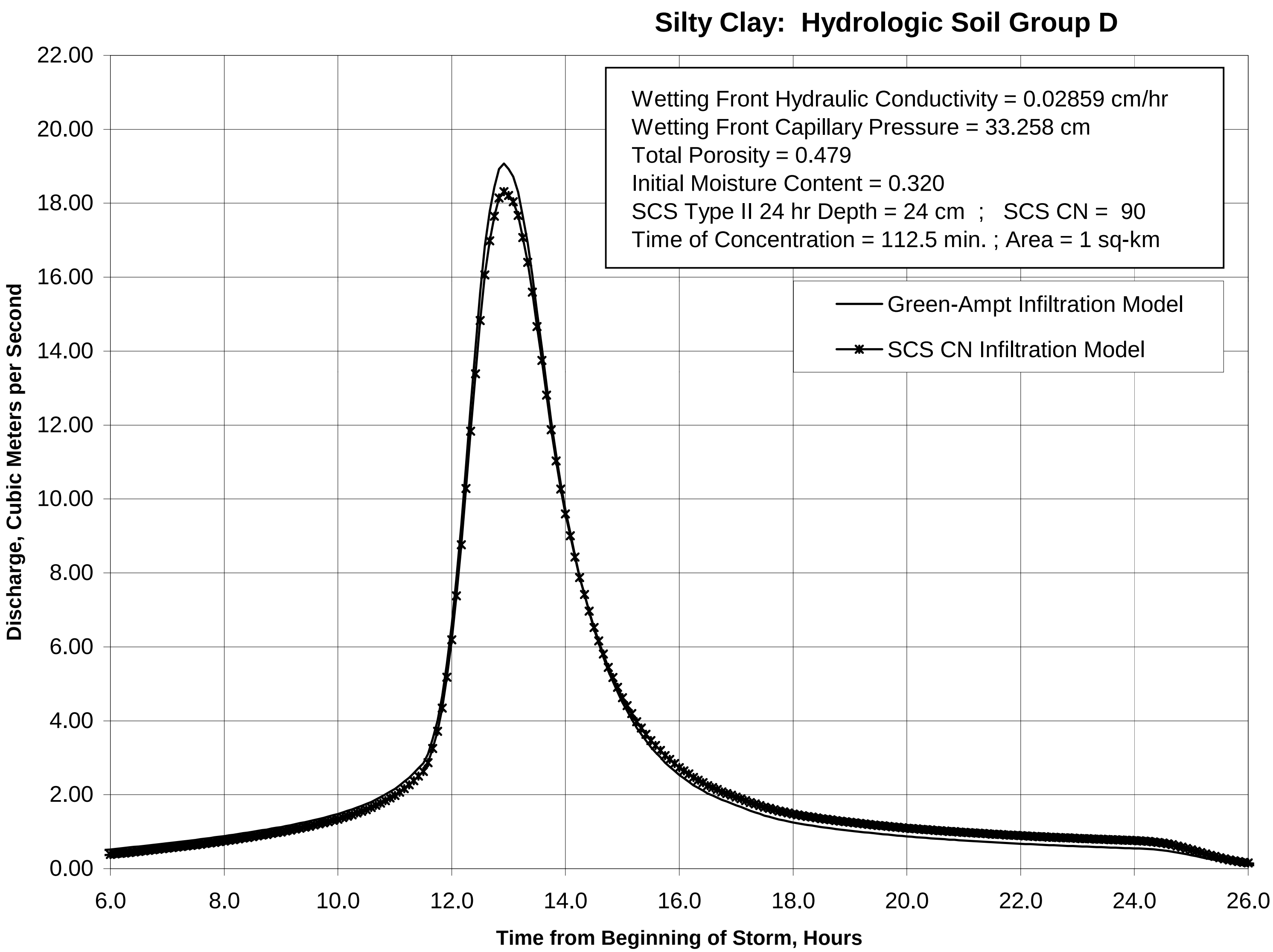

Figure A.45 Equal Volume Runoff Hydrographs, 24 cm Storm Depth, CN = 90, Tc = 112.5 min.

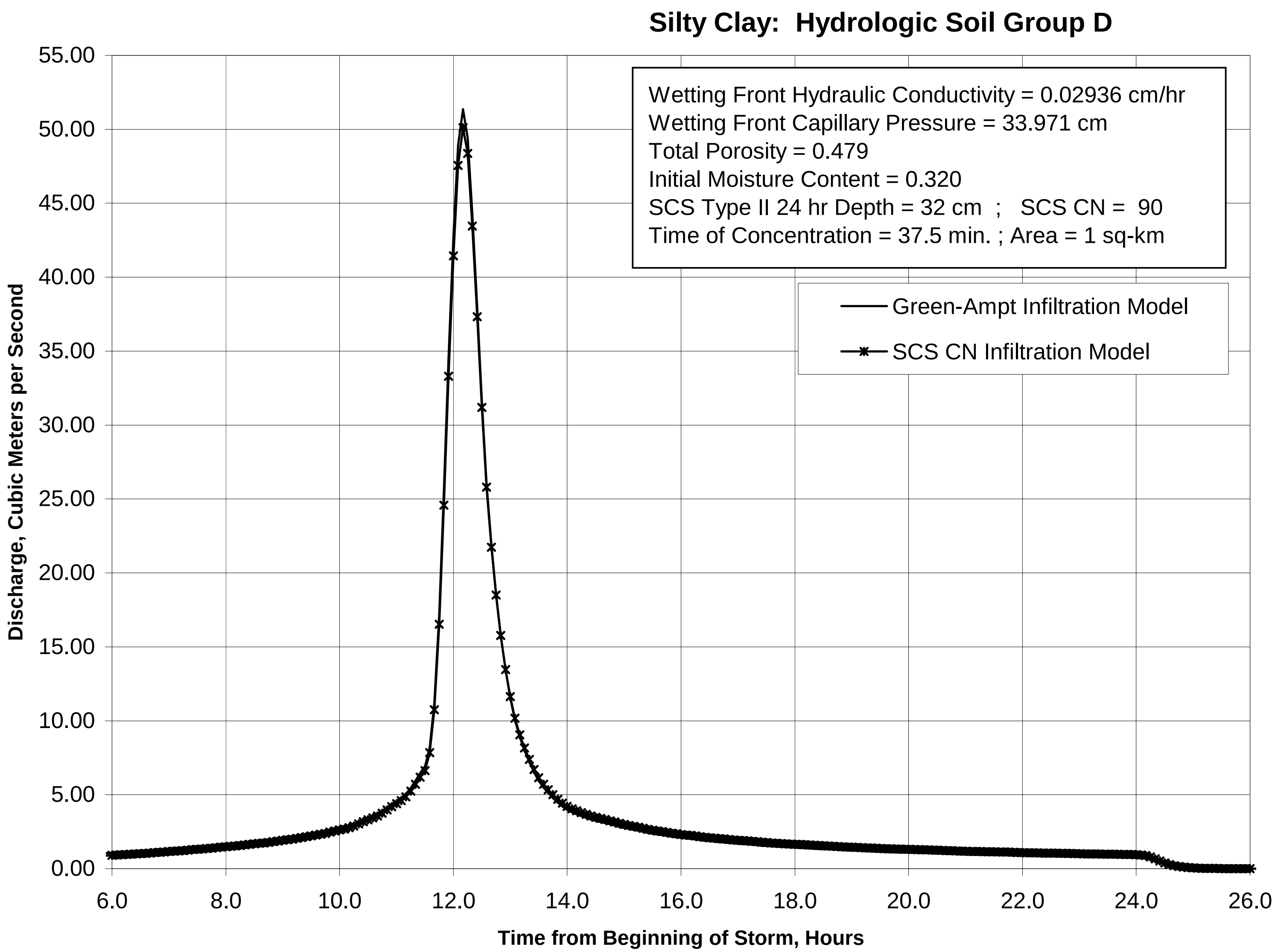

Figure A.46 Equal Volume Runoff Hydrographs, 32 cm Storm Depth, CN = 90, Tc = 37.5 min.

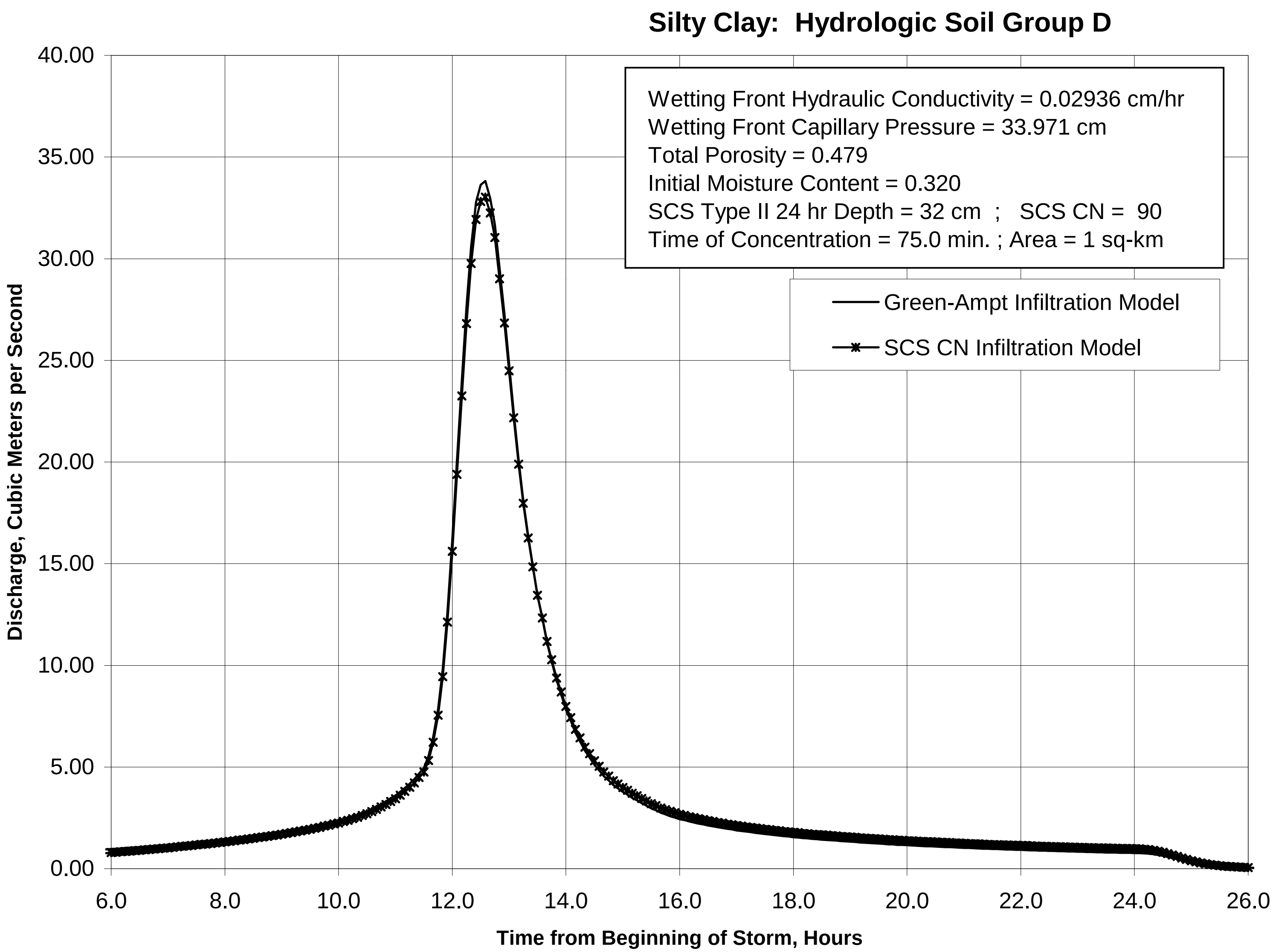

Figure A.47 Equal Volume Runoff Hydrographs, 32 cm Storm Depth, CN = 90, Tc = 75.0 min.

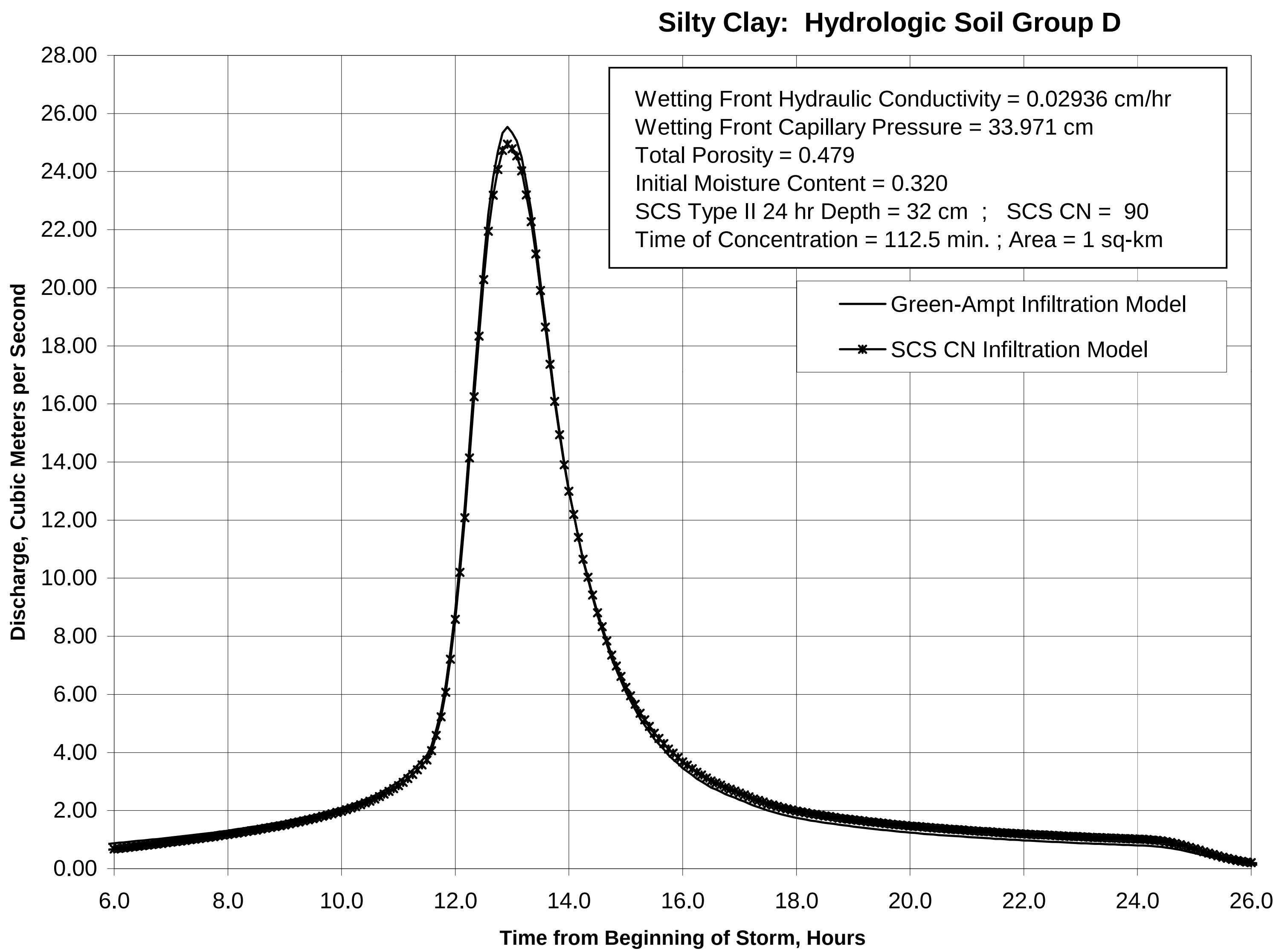

Figure A.48 Equal Volume Runoff Hydrographs, 32 cm Storm Depth, CN = 90, Tc = 112.5 min.

APPENDIX B

ACCUMULATED INFILTRATION

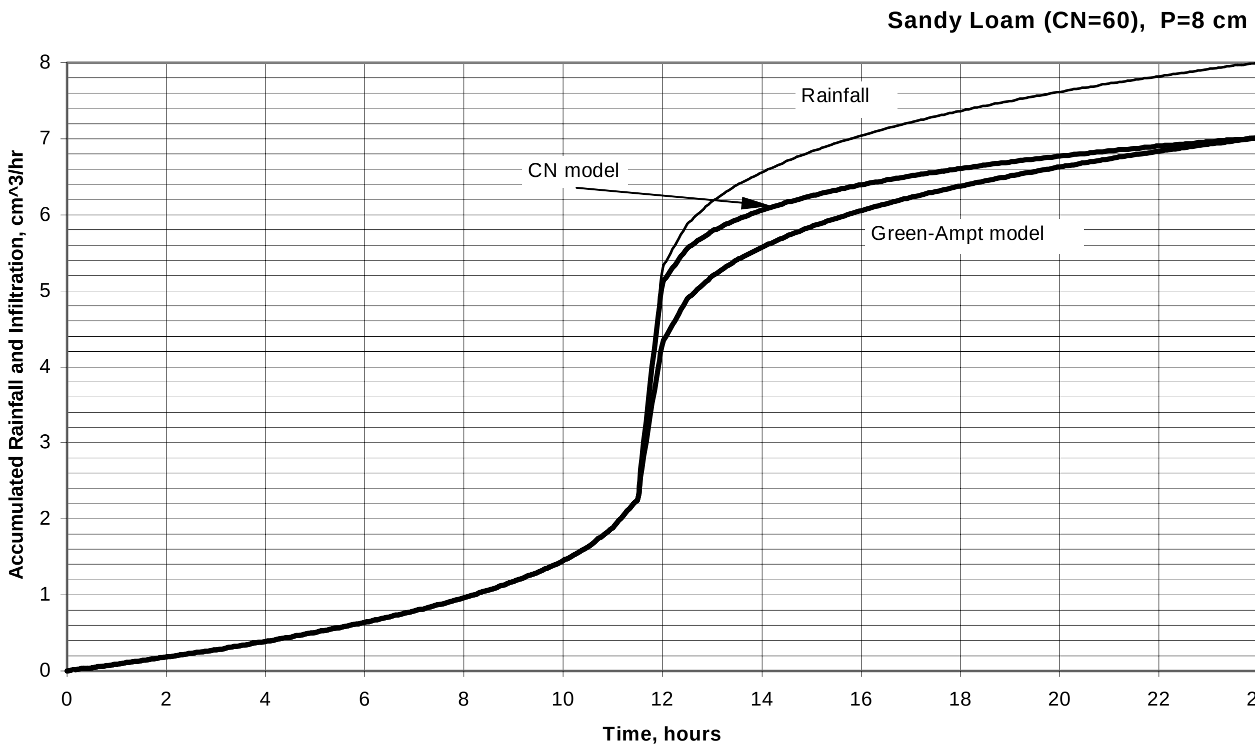

Figure B.1 Green-Ampt and SCS CN accumulated infiltration (Sandy Loam, P=8 cm)

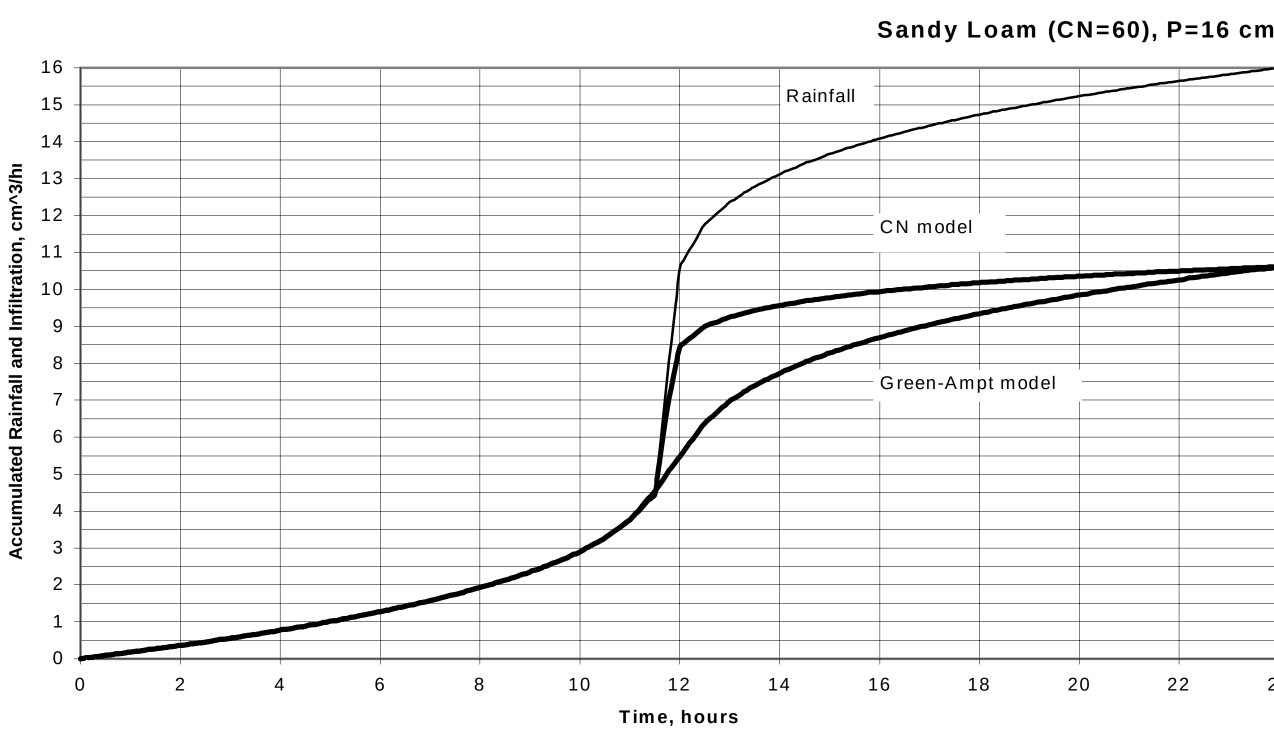

Figure B.2 Green-Ampt and SCS CN accumulated infiltration (Sandy Loam, P=16 cm)

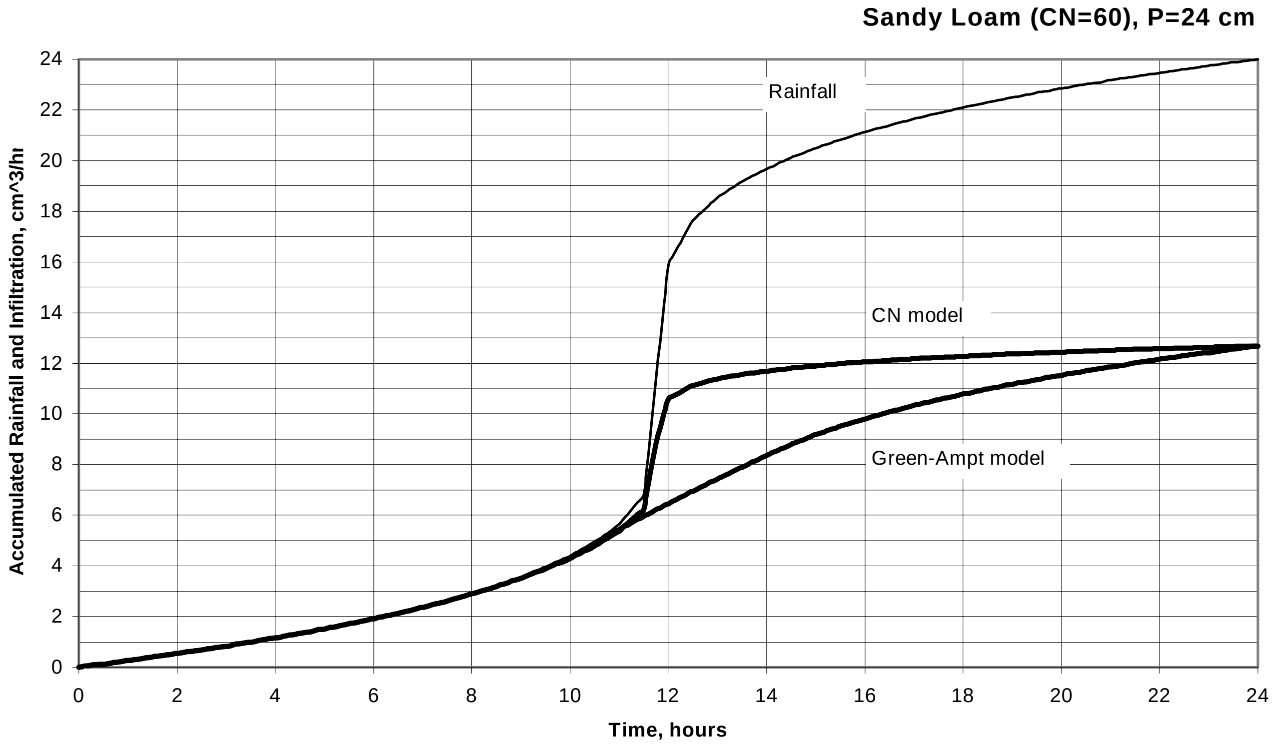

Figure B.3 Green-Ampt and SCS CN accumulated infiltration (Sandy Loam, P=24 cm)

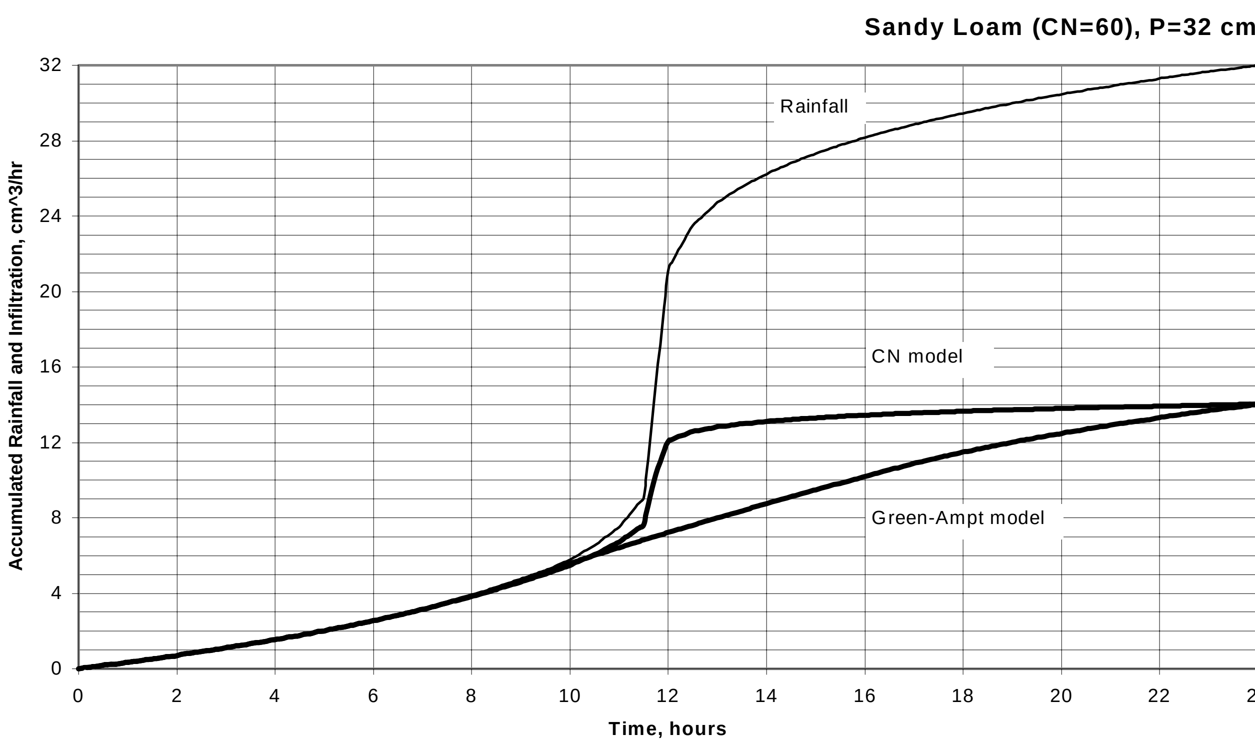

Figure B.4 Green-Ampt and SCS CN accumulated infiltration (Sandy Loam, P=32 cm)

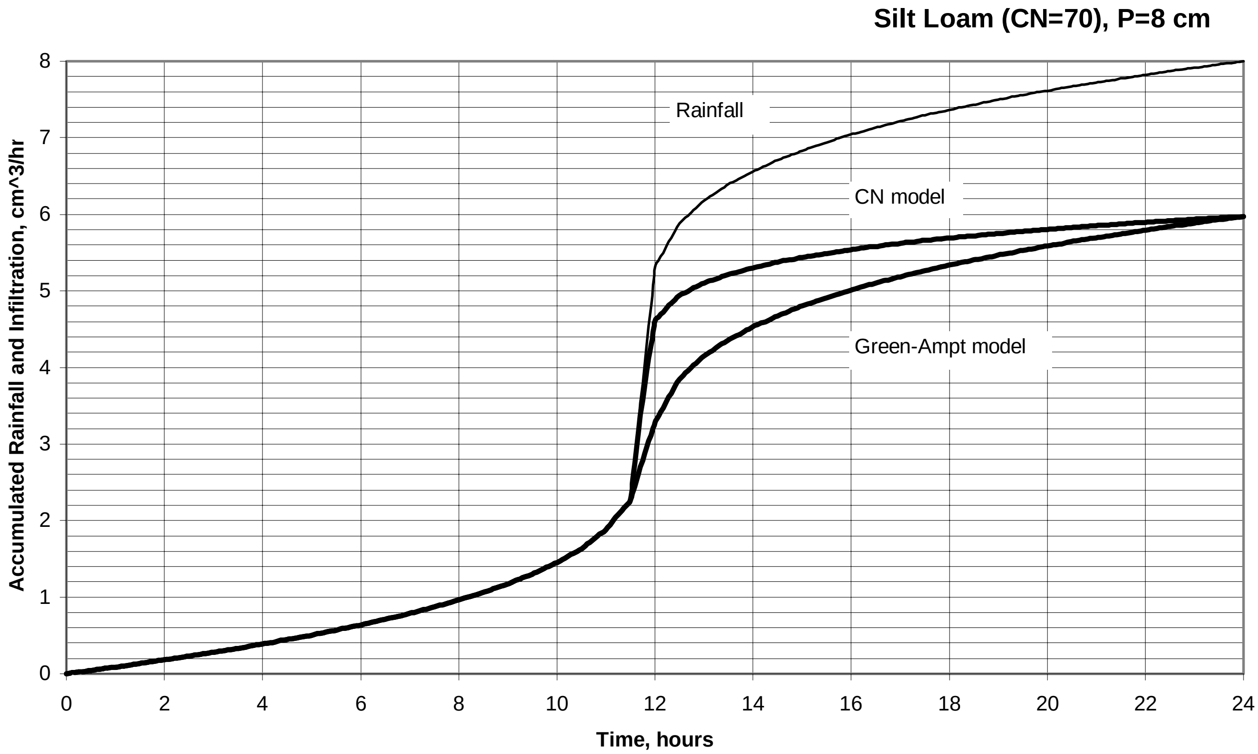

Figure B.5 Green-Ampt and SCS CN accumulated infiltration (Silt Loam, P=8 cm)

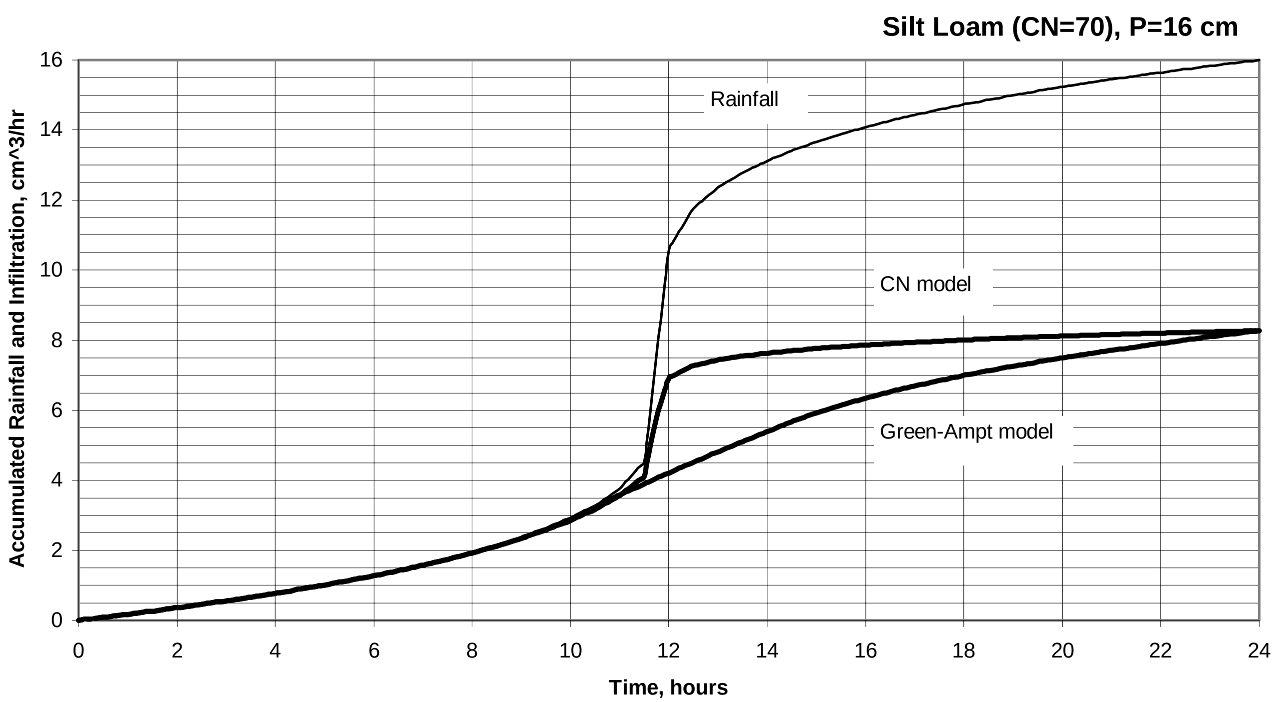

Figure B.6 Green-Ampt and SCS CN accumulated infiltration (Silt Loam, P=16 cm)

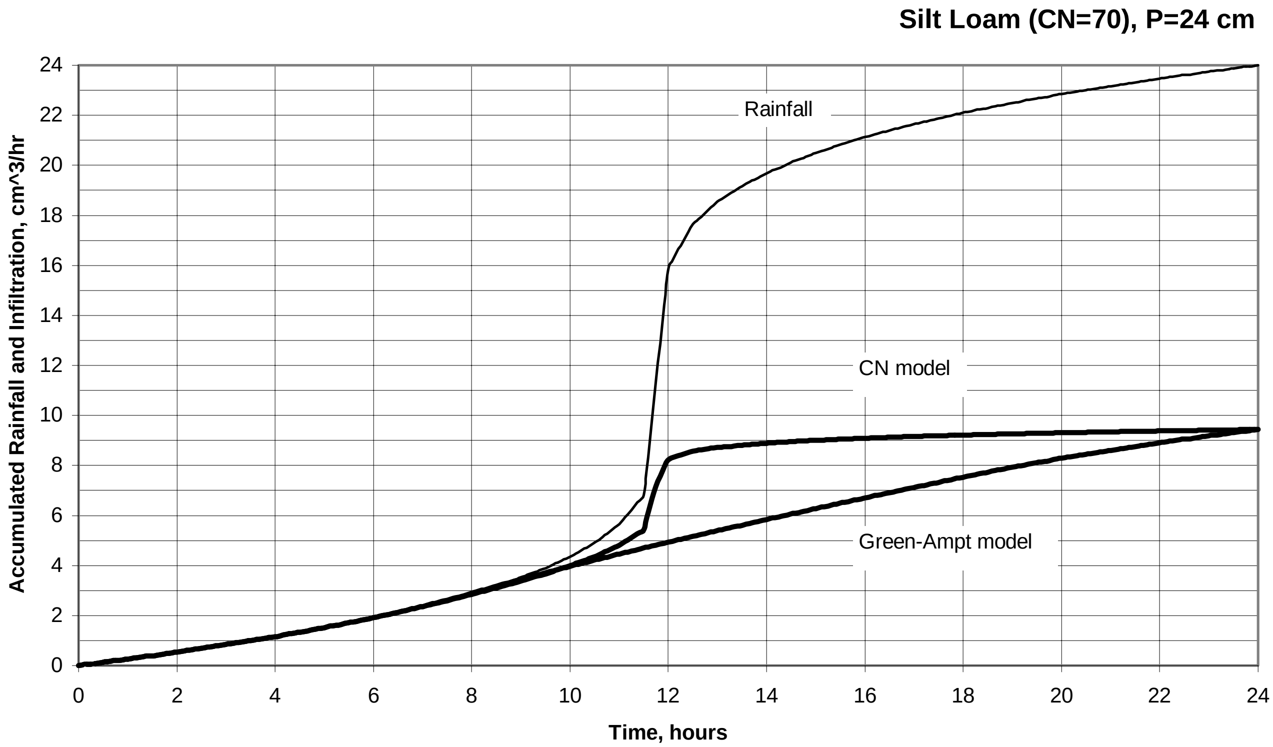

Figure B.7 Green-Ampt and SCS CN accumulated infiltration (Silt Loam, P=24 cm)

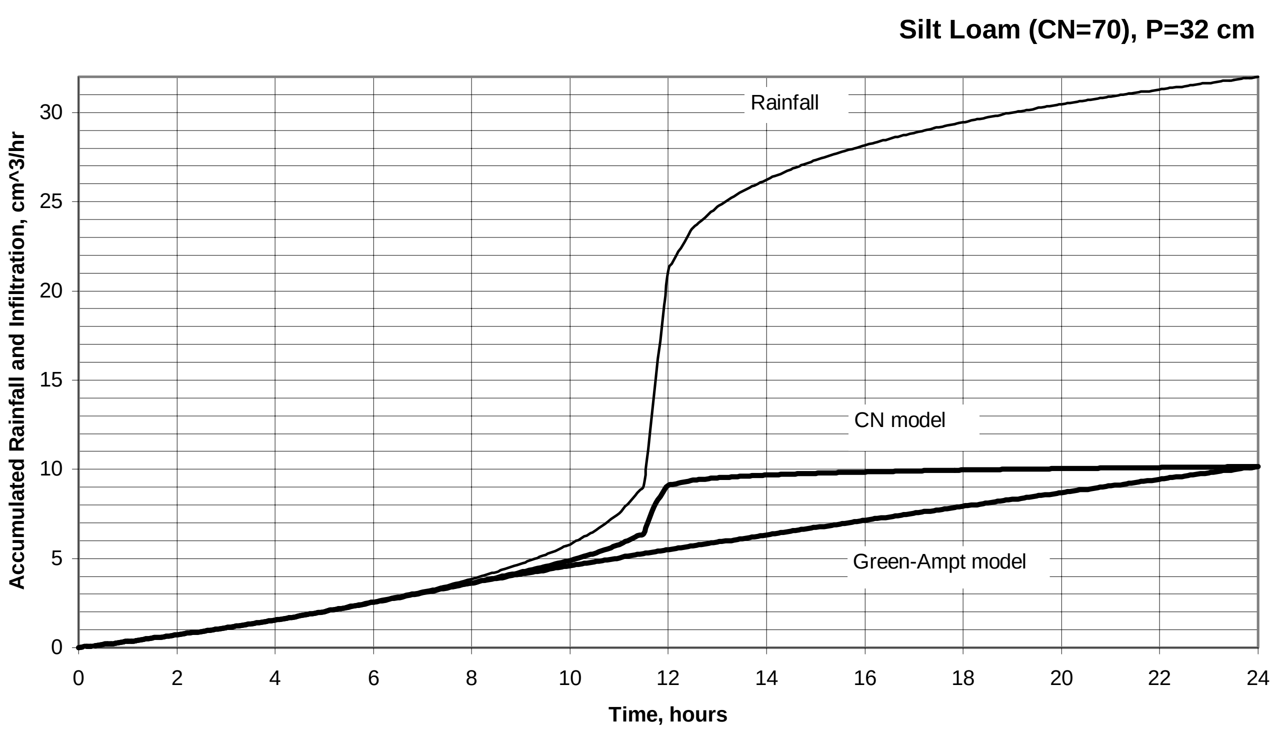

Figure B.8 Green-Ampt and SCS CN accumulated infiltration (Silt Loam, P=32 cm)

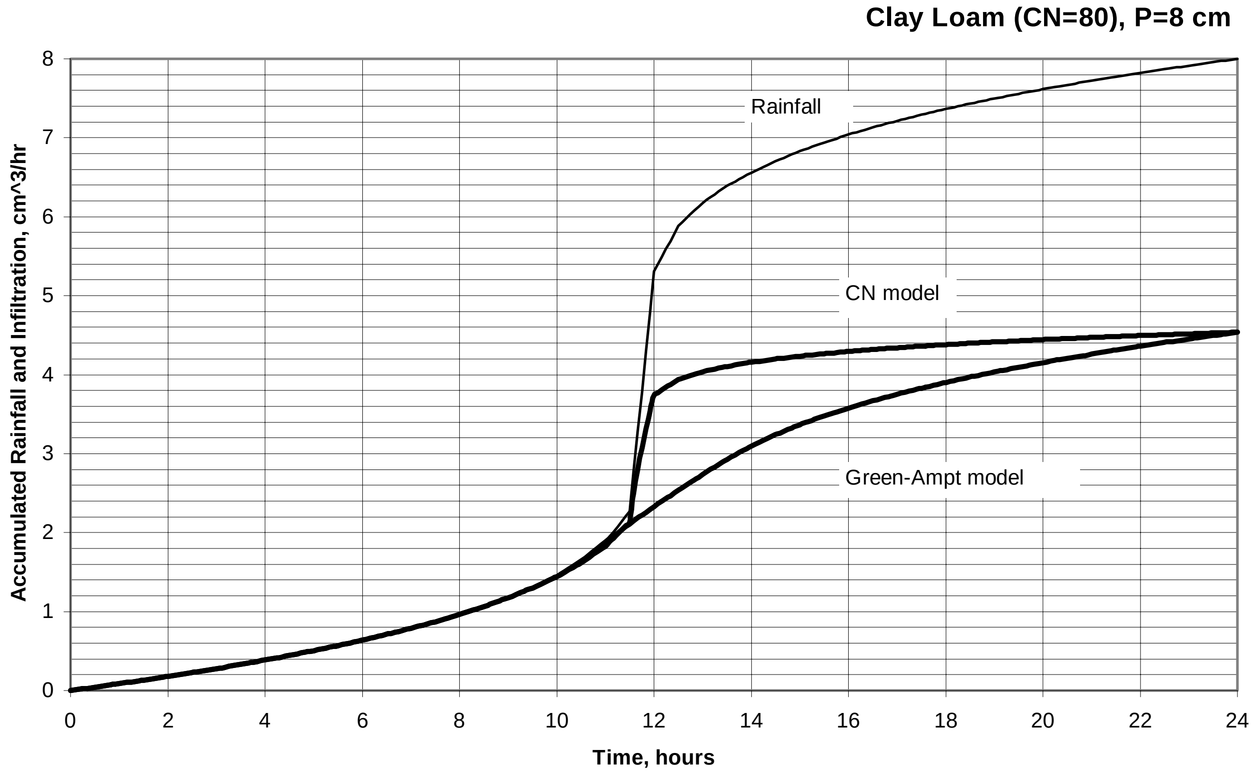

Figure B.9 Green-Ampt and SCS CN accumulated infiltration (Clay Loam, P=8 cm)

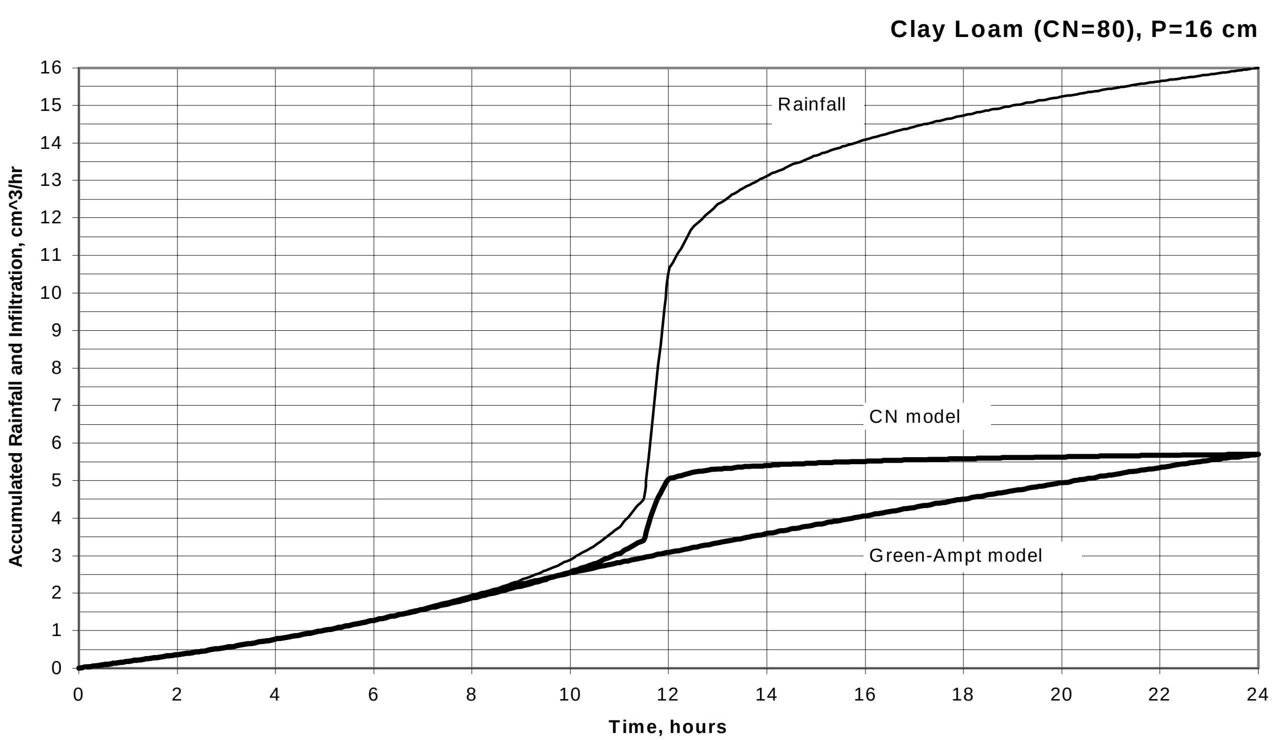

Figure B.10 Green-Ampt and SCS CN accumulated infiltration (Clay Loam, P=16 cm)

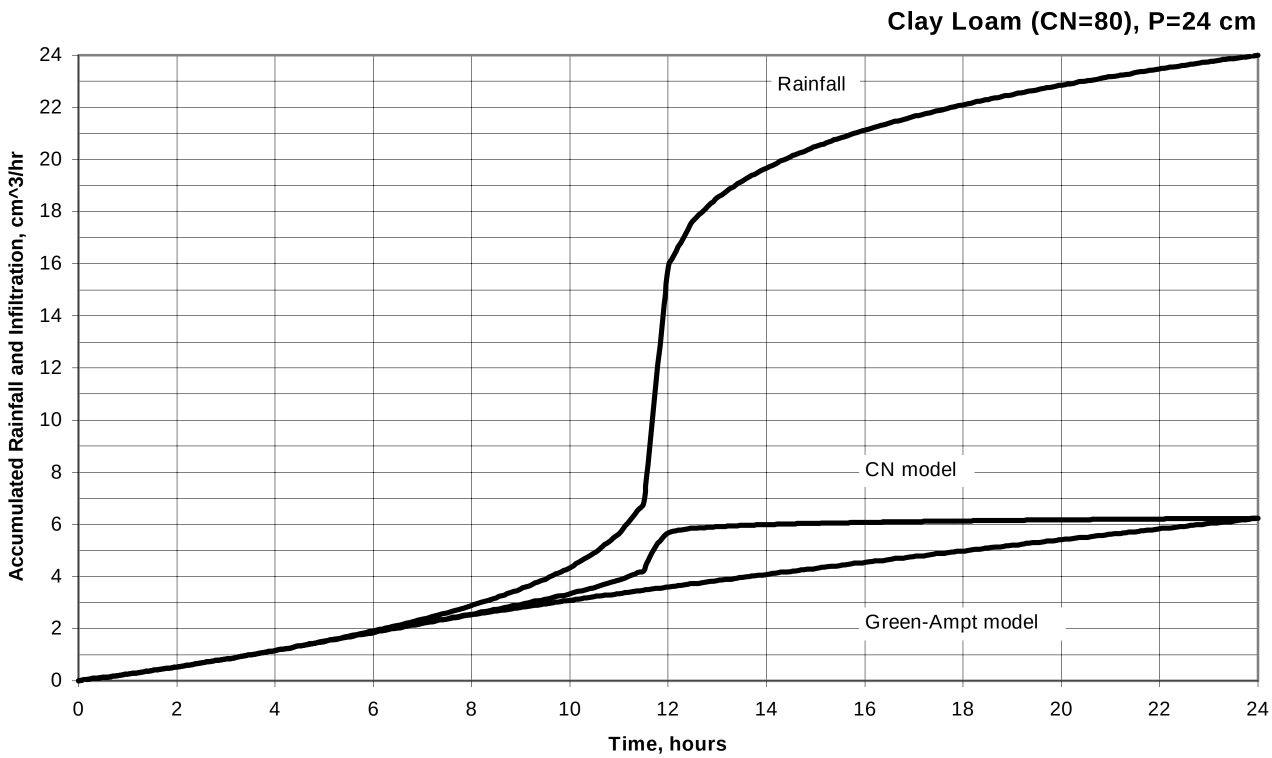

Figure B.11 Green-Ampt and SCS CN accumulated infiltration (Clay Loam, P=24 cm)

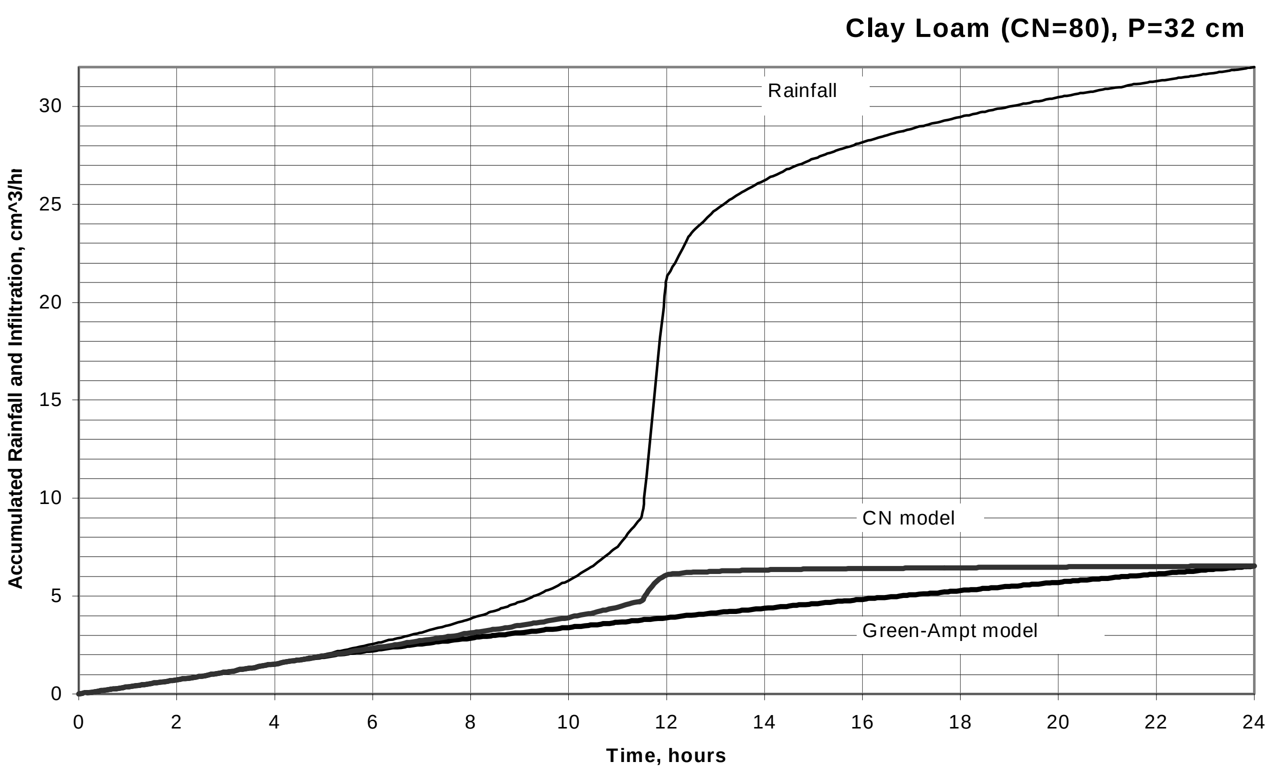

Figure B.12 Green-Ampt and SCS CN accumulated infiltration (Clay Loam, P=32 cm)

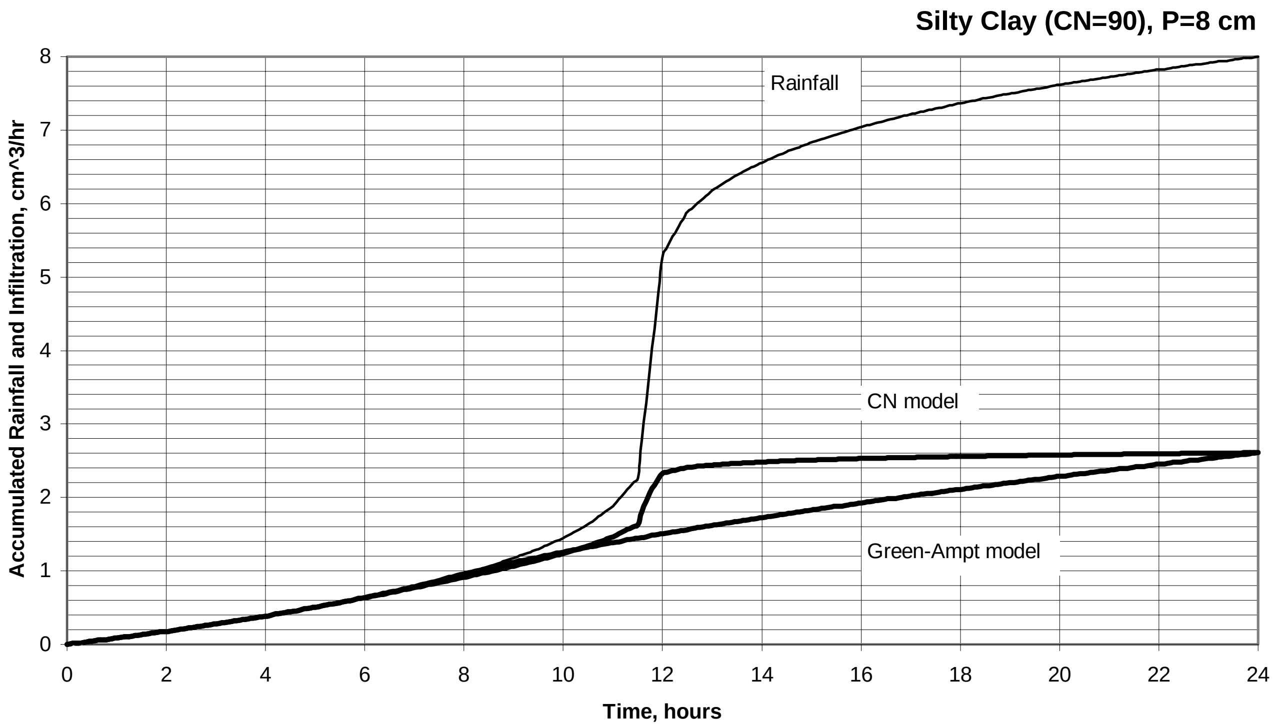

Figure B.13 Green-Ampt and SCS CN accumulated infiltration (Silty Clay, P=8 cm)

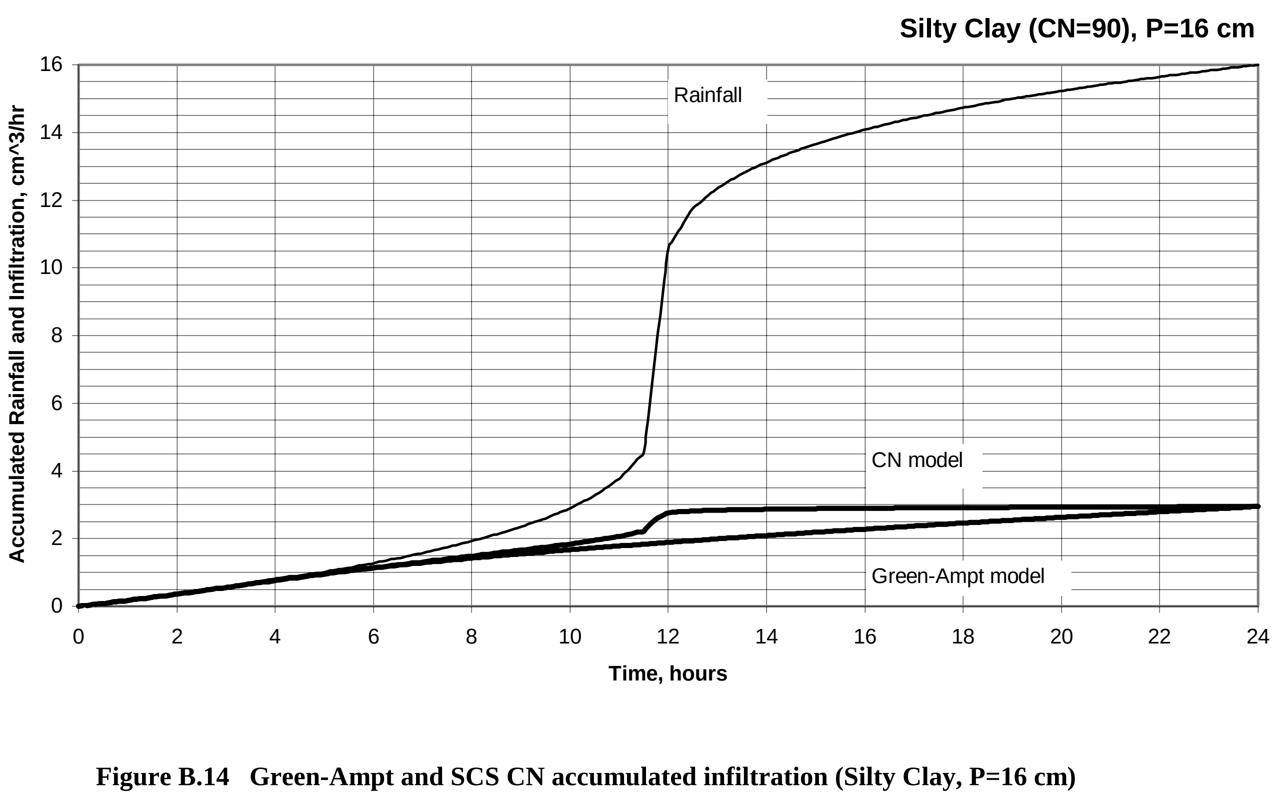

Figure B.14 Green-Ampt and SCS CN accumulated infiltration (Silty Clay, P=16 cm)

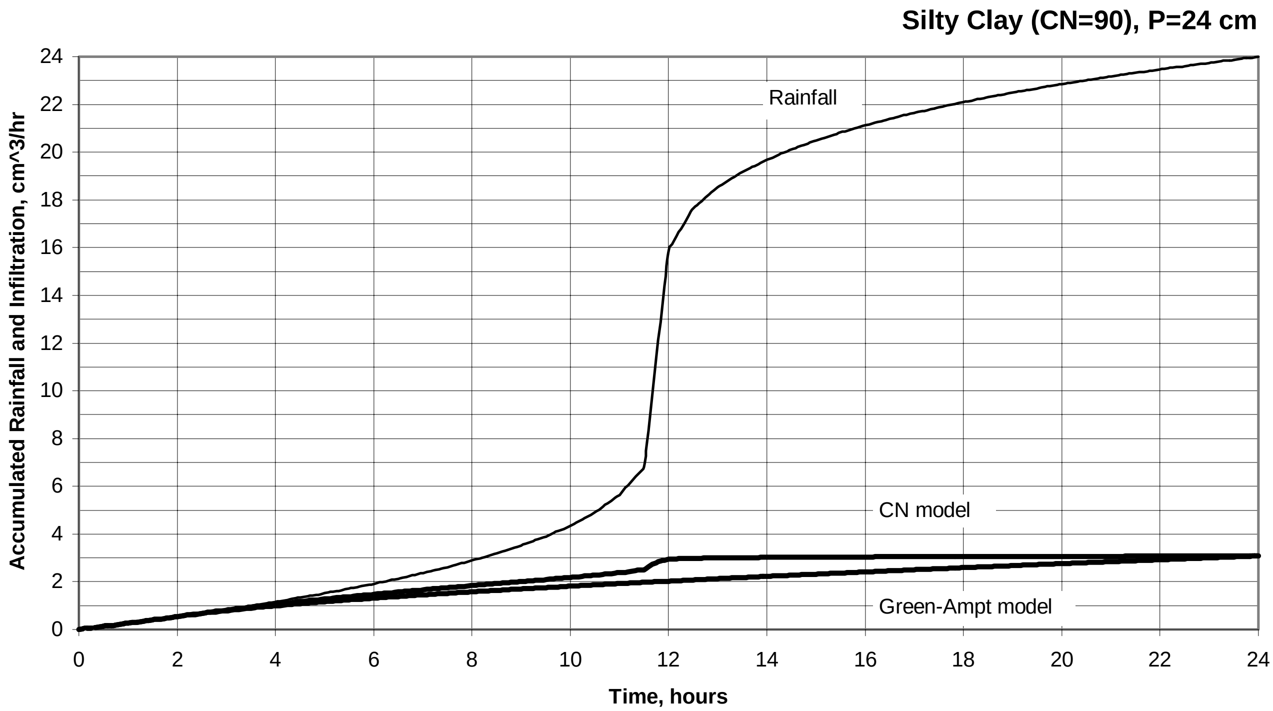

Figure B.15 Green-Ampt and SCS CN accumulated infiltration (Silty Clay, P=24 cm)

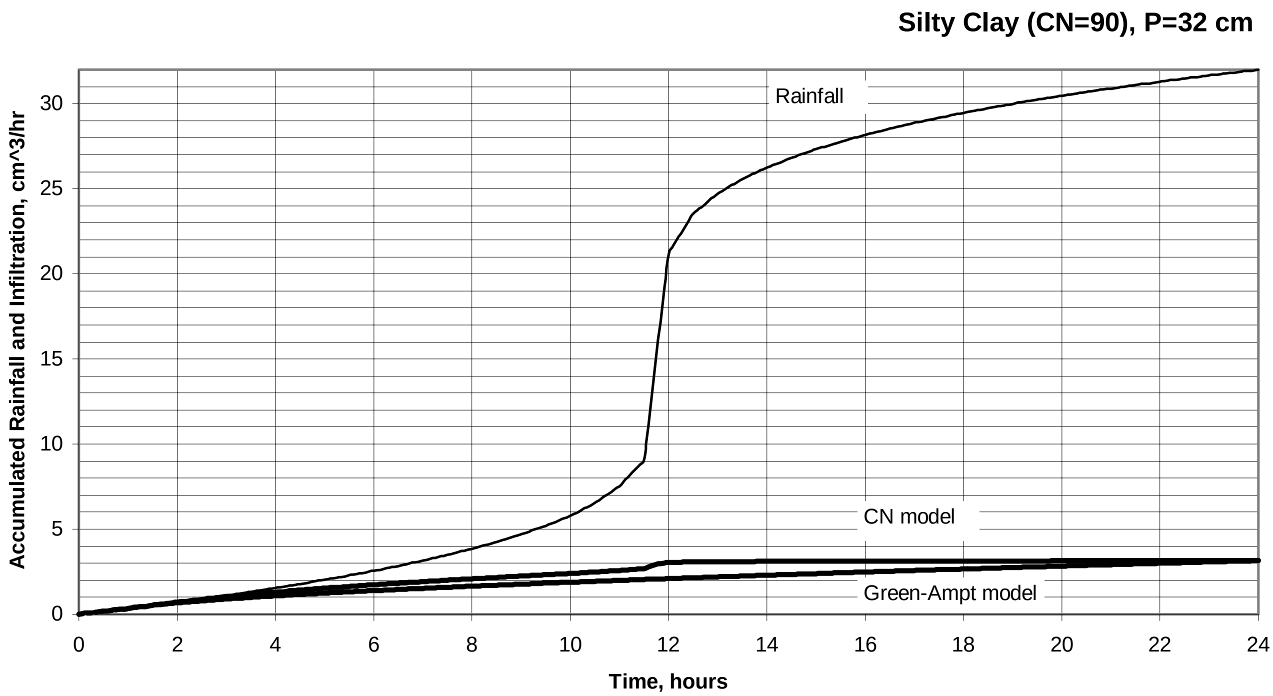

Figure B.16 Green-Ampt and SCS CN accumulated infiltration (Silty Clay, P=32 cm)

APPENDIX C

PROGRAMS

<GreenADlg.cpp>

```
// GreenADlg.cpp : implementation file
#include "stdafx.h"
#include "GreenA.h"
#include "GreenADlg.h"
#include <iostream.h>
#include <iomanip.h>
#include <ios.h>
#include <cmath>
#include <fstream.h>
#include <string.h>
#ifdef _DEBUG
#define new DEBUG_NEW
#undef THIS_FILE
static char THIS_FILE[] = __FILE__;
#endif
/////////////////////////////////////////////////////////////////////////////
// CAboutDlg dialog used for App About
class CAboutDlg : public CDialog
{
public:
	CAboutDlg();

// Dialog Data
	//{{AFX_DATA(CAboutDlg)
	enum { IDD = IDD_ABOUTBOX };
	//}}AFX_DATA

	// ClassWizard generated virtual function overrides
	//{{AFX_VIRTUAL(CAboutDlg)
	protected:
	virtual void DoDataExchange(CDataExchange* pDX);    // DDX/DDV support
	//}}AFX_VIRTUAL

// Implementation
protected:
	//{{AFX_MSG(CAboutDlg)
	//}}AFX_MSG
	DECLARE_MESSAGE_MAP()
};

CAboutDlg::CAboutDlg() : CDialog(CAboutDlg::IDD)
{
	//{{AFX_DATA_INIT(CAboutDlg)
	//}}AFX_DATA_INIT
}

void CAboutDlg::DoDataExchange(CDataExchange* pDX)
{
	CDialog::DoDataExchange(pDX);
	//{{AFX_DATA_MAP(CAboutDlg)
	//}}AFX_DATA_MAP
}
```

```
BEGIN_MESSAGE_MAP(CAboutDlg, CDialog)
	//{{AFX_MSG_MAP(CAboutDlg)
		// No message handlers
	//}}AFX_MSG_MAP
END_MESSAGE_MAP()

/////////////////////////////////////////////////////////////////////////////
// CGreenADlg dialog

CGreenADlg::CGreenADlg(CWnd* pParent /*=NULL*/)
	: CDialog(CGreenADlg::IDD, pParent)
{
	//{{AFX_DATA_INIT(CGreenADlg)
	m_Infile = _T("");
	m_Outfile = _T("");
	m_depth = 0.0;
	m_finish = _T("");
	m_KValue = 0.0;
	m_StormDist = -1;
	m_rfoutfile = _T("");
	m_ManAutoGaRadio = -1;
	m_Porosity = 0.0;
	m_SuctHead = 0.0;
	m_InitialMoist = 0.0;
	m_CompHead = 0.0;
	m_SCSCN = 0.0;
	m_SCSS = 0.0;
	m_SCSF24 = 0.0;
	m_SCSQ24 = 0.0;
	m_GAF24 = 0.0;
	//}}AFX_DATA_INIT
	// Note that LoadIcon does not require a subsequent DestroyIcon in Win32
	m_hIcon = AfxGetApp()->LoadIcon(IDR_MAINFRAME);
}

void CGreenADlg::DoDataExchange(CDataExchange* pDX)
{
	CDialog::DoDataExchange(pDX);
	//{{AFX_DATA_MAP(CGreenADlg)
	DDX_Text(pDX, IDC_INPUTFILE_EDIT_BOX, m_Infile);
	DDX_Text(pDX, IDC_OUTPUT_FILE_EDIT, m_Outfile);
	DDX_Text(pDX, IDC_DEPTH_EDIT, m_depth);
	DDV_MinMaxDouble(pDX, m_depth, 0., 100.);
	DDX_Text(pDX, IDC_FINISHED_EDIT, m_finish);
	DDX_Text(pDX, IDC_K_EDIT, m_KValue);
	DDV_MinMaxDouble(pDX, m_KValue, 0., 100.);
	DDX_Radio(pDX, IDC_UNIFORM_RADIO1, m_StormDist);
	DDX_Text(pDX, IDC_RFOUTPUT_FILE_EDIT, m_rfoutfile);
	DDX_Radio(pDX, IDC_MANUAL_GA_RADIO, m_ManAutoGaRadio);
	DDX_Text(pDX, IDC_POROSITY_EDIT, m_Porosity);
	DDV_MinMaxDouble(pDX, m_Porosity, 0., 0.8);
	DDX_Text(pDX, IDC_SUCT_HEAD_EDIT, m_SuctHead);
	DDV_MinMaxDouble(pDX, m_SuctHead, 0., 300.);
	DDX_Text(pDX, IDC_INITIAL_MOISTURE_EDIT, m_InitialMoist);
	DDV_MinMaxDouble(pDX, m_InitialMoist, 0., 0.8);
```

```
	DDX_Text(pDX, IDC_COMP_HEAD_EDIT, m_CompHead);
	DDX_Text(pDX, IDC_SCS_CN_EDIT, m_SCSCN);
	DDX_Text(pDX, IDC_POT_MAX_RET_EDIT, m_SCSS);
	DDX_Text(pDX, IDC_GA_SCS_F24_EDIT, m_SCSF24);
	DDX_Text(pDX, IDC_GA_SCS_Q24_EDIT, m_SCSQ24);
	DDX_Text(pDX, IDC_GA_INFILT_EDIT, m_GAF24);
	//}}AFX_DATA_MAP
}

BEGIN_MESSAGE_MAP(CGreenADlg, CDialog)
	//{{AFX_MSG_MAP(CGreenADlg)
	ON_WM_SYSCOMMAND()
	ON_WM_PAINT()
	ON_WM_QUERYDRAGICON()
	ON_BN_CLICKED(IDC_EXIT_BUTTON, OnExitButton)
	ON_BN_CLICKED(IDC_START_BUTTON, OnStartButton)
	ON_BN_CLICKED(IDC_REENTER_BUTTON, OnReenterButton)
	ON_BN_CLICKED(IDC_CHG_OUTFILE_BUTTON, OnChgOutfileButton)
	ON_BN_CLICKED(IDC_RFOUTFILE_DEFAULT_BUTTON, OnRfoutfileDefaultButton)
	//}}AFX_MSG_MAP
END_MESSAGE_MAP()

/////////////////////////////////////////////////////////////////////////////
// CGreenADlg message handlers

BOOL CGreenADlg::OnInitDialog()
{
	CDialog::OnInitDialog();

	// Add "About..." menu item to system menu.

	// IDM_ABOUTBOX must be in the system command range.
	ASSERT((IDM_ABOUTBOX & 0xFFF0) == IDM_ABOUTBOX);
	ASSERT(IDM_ABOUTBOX < 0xF000);

	CMenu* pSysMenu = GetSystemMenu(FALSE);
	if (pSysMenu != NULL)
	{
		CString strAboutMenu;
		strAboutMenu.LoadString(IDS_ABOUTBOX);
		if (!strAboutMenu.IsEmpty())
		{
			pSysMenu->AppendMenu(MF_SEPARATOR);
			pSysMenu->AppendMenu(MF_STRING, IDM_ABOUTBOX, strAboutMenu);
		}
	}

	// Set the icon for this dialog.  The framework does this automatically
	//  when the application's main window is not a dialog
	SetIcon(m_hIcon, TRUE);			// Set big icon
	SetIcon(m_hIcon, FALSE);		// Set small icon

	// TODO: Add extra initialization here
	m_Infile="c:\\cprograms\\SCSII_uniform_rf_dist.dat";
	m_Outfile="c:\\cprograms\\infilt_output.dat";
	m_rfoutfile="c:\\cprograms\\rainfall_output.dat";
```

```
	m_depth=18.0;
	m_finish="Enter Filenames & Data";
	m_KValue=0.3;
	m_StormDist=0;
	m_ManAutoGaRadio=1;
	m_Porosity=0.5;
	m_InitialMoist=0.1;
	m_SuctHead=8.0;
	UpdateData(FALSE);

	return TRUE;  // return TRUE  unless you set the focus to a control
}

void CGreenADlg::OnSysCommand(UINT nID, LPARAM lParam)
{
	if ((nID & 0xFFF0) == IDM_ABOUTBOX)
	{
		CAboutDlg dlgAbout;
		dlgAbout.DoModal();
	}
	else
	{
		CDialog::OnSysCommand(nID, lParam);
	}
}

void CGreenADlg::OnPaint()
{
	if (IsIconic())
	{
		CPaintDC dc(this); // device context for painting

		SendMessage(WM_ICONERASEBKGND, (WPARAM) dc.GetSafeHdc(), 0);

		// Center icon in client rectangle
		int cxIcon = GetSystemMetrics(SM_CXICON);
		int cyIcon = GetSystemMetrics(SM_CYICON);
		CRect rect;
		GetClientRect(&rect);
		int x = (rect.Width() - cxIcon + 1) / 2;
		int y = (rect.Height() - cyIcon + 1) / 2;

		// Draw the icon
		dc.DrawIcon(x, y, m_hIcon);
	}
	else
	{
		CDialog::OnPaint();
	}
}

HCURSOR CGreenADlg::OnQueryDragIcon()
{
	return (HCURSOR) m_hIcon;
}
```

```
void CGreenADlg::OnExitButton()
{
	// TODO: Add your control notification handler code here
	OnOK();
}

void CGreenADlg::OnStartButton()
{
	// TODO: Add your control notification handler code here
	// Open Input file and Output:
	UpdateData(TRUE);
	Infile1=m_Infile;
	Outfile1=m_Outfile;
	Outfile2=m_rfoutfile;
	ifstream raindist(m_Infile,ios::in);
	if(raindist.fail())
	{
		m_Infile="::file open failed, reenter correct filename";
		UpdateData(FALSE);
	}
	ofstream infiltrate(m_Outfile);
	if(infiltrate.fail())
	{
		m_Outfile="::file open failed, reenter correct filename";
		UpdateData(FALSE);
	}
	ofstream rainfall(m_rfoutfile);
	if(rainfall.fail())
	{
		m_rfoutfile="::file open failed, reenter correct filename";
		UpdateData(FALSE);
	}
 if(raindist.fail()||infiltrate.fail()||rainfall.fail())
 {
	m_finish="Execution Failed: Bad Filename";
	UpdateData(FALSE);
 }
 else
 {
	m_finish=" ";
	UpdateData(FALSE);
// MFCinfilt/GreenA.exe version 1.13 3-8-2001.
// derived from MFCgampt workspace and greenampt.cpp
// MFCinfilt copied from MFCgampt workspace on 11-11-2000,
// for modification to output rainfall and infiltration rates,
// for 5 min time intervals over 24 hours.
// greenampt.cpp version 1.09, 5/29/2000.
// greenampt infiltration for any i(t) using 288 equal time increments.
// modified for single storm depth only (m=0)
	double i[288],f[289],F[289],fpot[289],dt,psi,dtheta,logpsi,logK,ci[5][49];
	double F1,F2,DF,Fpond[289],dtp,P,K,F24,R,Q24,CN,cd[48],iplot[576],Q[289];
	double cd5[288],t,I[289],time[289],S,S1,S2,Sminus,Splus,fave,Ia;
	double tpond[289],fpond[289],fplot[576],f_CN[289],F_CN[289],Fpond_CN[289];
	double Q_CN[289],tpond_CN[289],fpond_CN[289],fplot_CN[576];
	long int m,n,k,kk;
	dt=1.0/12.0;					//set dt=1/12 hr (5 min. intervals).
```

```
	dtheta=m_Porosity-m_InitialMoist; //compute dtheta.
	K=m_KValue;							//load hydraulic
conductivity, K, cm/hr.
	P=m_depth;							//load storm depth, cm.
	m=m_StormDist;						//load storm dist. number from
radio button.
	// 0=uniform, 1=TypeI, 2=TypeIA, 3=TypeII, 4=TypeIII
	R=2.54;								//enter inches to cm
conversion.
	kk=0;
	for(n=0;n<49;n++)
	{
		//read in cumulative rf distributions, 0.5 hr increments.
		raindist >>t>>ci[0][n]>>ci[1][n]>>ci[2][n]>>ci[3][n]>>ci[4][n];
		if(n>0)
		{
			cd[n-1]=ci[m][n]-ci[m][n-1];	//compute differential accumlation.
			for(k=0;k<6;k++)
			{
				cd5[kk]=cd[n-1]/6.0;	//compute 5 min. accumulations.
				kk++;
			}
		}
	}
		kk=0;
		for(k=0;k<288;k++)
		{
			i[k]=P*cd5[k]/dt;			//load rainfall rate for storm depth, cm/hr.
			iplot[kk]=i[k];				//load rainfall hyetograph.
			iplot[++kk]=i[k];
			kk++;
		}
	if(m_ManAutoGaRadio==1)				//if autocompute of psi is desired.
	{
		logK=log10(K);
		logpsi=-0.3266*logK+1.0177;
		psi=pow(10.0,logpsi);
		m_CompHead=psi;					//load edit window with
autocompute value.
	}
	else								//if manual input of psi is desired.
	{
		psi=m_SuctHead;
		m_CompHead=0.0;					//zero autocompute edit window
	}
	fpot[0]=99999.;					//assign a large initial potential infiltration.
	F[0]=0.0;							//assign initial accumulated infiltration.
	Q[0]=0.0;							//assign initial accumulated runoff.
	I[0]=0.0;						//assign initial accumulated rainfall.
	f[0]=i[0];							//set initial infiltration rate = rainfall rate.
	time[0]=0.0;					//initialize the time counter.
	Fpond[0]=Fpond[288]=0.0;		//set intial and final ponding parameters.
	tpond[0]=tpond[288]=0.0;
	fpond[0]=fpond[288]=0.0;
	kk=0;
  for(n=0;n<288;n++)
```

```
 {
        time[n+1]=(n+1)*dt;
        if(fpot[n]<=i[n])
        {
                //ponding throughout the interval:
                Fpond[n]=F[n];                  //store accumulated infiltration at ponding.
                tpond[n]=time[n];               //store time at ponding.
                fpond[n]=f[n];                  //store infiltration rate at ponding.
                //iterate to find F[n+1]:
                F1=F[n]+K*dt;                                   //set initial value.
                do
                {
                        F2=F[n]+K*dt+psi*dtheta*log((F1+psi*dtheta)/(F[n]+psi*dtheta));
                        DF=fabs(F2-F1);
                        F1=F2;
                }
                while(DF>0.000001);
                F[n+1]=F2;                                      //compute new infiltration
depth.
                fpot[n+1]=K*(psi*dtheta/F[n+1]+1);
        }
        else
        {
                //calculate tentative values of F[n+1] & fpot[n+1]
                F[n+1]=F[n]+i[n]*dt;
                fpot[n+1]=K*(psi*dtheta/F[n+1]+1);
                if(fpot[n+1]<=i[n])
                {
                        //ponding occurs during interval
                        Fpond[n]=K*psi*dtheta/(i[n]-K);         //compute F at ponding point.
                        dtp=(Fpond[n]-F[n])/i[n];               //compute ponding delta t.
                        tpond[n]=time[n]+dtp;                           //compute time of
ponding.
                        fpond[n]=i[n];                                  //set infiltration rate at
ponding.
                        //iterate to find F[n+1]:
                        F1=Fpond[n]+K*(dt-dtp);                 //set initial value.
                        do
                        {
                                F2=Fpond[n]+K*(dt-
dtp)+psi*dtheta*log((F1+psi*dtheta)/(Fpond[n]+psi*dtheta));
                                DF=fabs(F2-F1);
                                F1=F2;
                        }
                        while(DF>0.000001);
                        F[n+1]=F2;                                      //store new infiltration
depth.
                }
                else
                {
                        //no ponding during interval
                        Fpond[n]=0.0;                           //reset Fpond to zero for no
ponding.
                        tpond[n]=0.0;                           //reset tpond to zero for no
ponding.
```

```
                        fpond[n]=0.0;                           //reset fpond to zero for no
ponding.
                        F[n+1]=F[n]+i[n]*dt;                //compute new infiltration depth.
                }
        }
        f[n+1]=K*(psi*dtheta/F[n+1]+1);             //compute instantaneous potential infiltration rate.
        if(f[n+1]>=i[n])f[n+1]=i[n];                //assign actual infiltration rate at n+1.
        fave=(F[n+1]-F[n])/dt;                              //compute average infiltration rate for dt.
        fplot[kk]=fave;                                     //set leading edge of fplot bar.
        fplot[++kk]=fave;                                   //set trailing edge of fplot bar.
        kk++;
        I[n+1]=i[n]*dt+I[n];                                //compute accumulated rainfall.
        Q[n+1]=I[n+1]-F[n+1];                                       //compute accumulated runoff.
        if(Q[n+1]<0.0)Q[n+1]=0.0;
 }
 Q24=P-F[288];
 if(Q24<0.000001)Q24=0.0;
 m_dlg.m_Q24check=Q24;
 S1=0.4*P+0.8*Q24;
 S2=pow((0.4*P+0.8*Q24),2.0)-0.16*(P*P-Q24*P);
 if(S2<0.0)
 {
         S=9999.0;
         CN=9999.0;
         Splus=S1;
         Sminus=S2;
 }
 else
 {
         Splus=(S1+sqrt(S2))/0.08;
         if(Splus<0.000001)Splus=0.0;
         Sminus=(S1-sqrt(S2))/0.08;
         if(Sminus<0.000001)Sminus=0.0;
         if((Sminus>=0.0)&&(P-Q24-0.2*Sminus>=0.0))
         {
                 S=Sminus;
         }
         else if((Splus>=0.0)&&(P-Q24-0.2*Splus>=0.0))
         {
                 S=Splus;
         }
         else
         {
                 S=99999.0;
                 CN=99999.0;
         }
         if(S<99998.0)
         {
         CN=(1000.0*R)/(S+10.0*R);
         if(CN<0.00001)CN=0.0;
         }
 }
        F24=P-Q24-0.2*S;
        F_CN[0]=0.0;                                        //set initial accum. infilt. to zero.
        Q_CN[0]=0.0;                                        //set initial accum. runoff to zero.
        f_CN[0]=0.0;                                        //set initial infilt. rate to zero.
```

```
        Fpond_CN[0]=Fpond_CN[288]=0.0;          //set initial and final ponding values.
        tpond_CN[0]=tpond_CN[288]=0.0;
        fpond_CN[0]=fpond_CN[288]=0.0;
        Ia=0.2*S;                                                //compute initial abstraction.
        kk=0;
        for(n=0;n<288;n++)
        {
                if((I[n]-Ia)>=0.0)                  //ponding throughout interval.
                {
                        Q_CN[n+1]=(I[n+1]-Ia)*(I[n+1]-Ia)/(I[n+1]-Ia+S);
                        f_CN[n+1]=S*S*i[n]/((I[n+1]-Ia+S)*(I[n+1]-Ia+S));
                        F_CN[n+1]=(I[n+1]-Ia)-Q_CN[n+1];
                        tpond_CN[n]=time[n];
                        fpond_CN[n]=f_CN[n];
                        Fpond_CN[n]=F_CN[n];
                }
                else if((I[n+1]-Ia)>0.0)    //ponding during interval.
                {
                        dtp=(Ia-I[n])/i[n];
                        tpond_CN[n]=time[n]+dtp;
                        fpond_CN[n]=i[n];
                        Q_CN[n+1]=(I[n+1]-Ia)*(I[n+1]-Ia)/(I[n+1]-Ia+S);
                        f_CN[n+1]=S*S*i[n]/((I[n+1]-Ia+S)*(I[n+1]-Ia+S));
                        F_CN[n+1]=(I[n+1]-Ia)-Q_CN[n+1];
                        Fpond_CN[n]=0.0;
                }
                else                                                    //no ponding.
                {
                        tpond_CN[n]=0.0;
                        fpond_CN[n]=0.0;
                        Fpond_CN[n]=0.0;
                        Q_CN[n+1]=0.0;
                        F_CN[n+1]=0.0;
                        f_CN[n+1]=0.0;
                }
                fave=(F_CN[n+1]-F_CN[n])/dt;
                fplot_CN[kk]=fave;
                fplot_CN[++kk]=fave;
                kk++;
        }
        for(n=0;n<289;n++)
{
          infiltrate        <<setiosflags(ios::fixed)<<setw(10)
                                    <<time[n]
                                    <<setw(10)
                                    <<f[n]
                                    <<setw(10)
                                    <<F[n]
                                    <<setw(10)
                                    <<I[n]
                                    <<setw(10)
                                    <<Q[n]
                                    <<setw(10)
                                    <<tpond[n]
                                    <<setw(10)
                                    <<fpond[n]
```

```
                                                  <<setw(10)
                                                  <<Fpond[n]
                                                  <<setw(10)
                                                  <<f_CN[n]
                                                  <<setw(10)
                                                  <<F_CN[n]
                                                  <<setw(10)
                                                  <<I[n]
                                                  <<setw(10)
                                                  <<Q_CN[n]
                                                  <<setw(10)
                                                  <<tpond_CN[n]
                                                  <<setw(10)
                                                  <<fpond_CN[n]
                                                  <<setw(10)
                                                  <<Fpond_CN[n]
                                                  <<endl;
    }
    kk=0;
    for(k=0;k<288;k++)
    {
            rainfall        <<setiosflags(ios::fixed)<<setw(10)
                                        <<time[k]
                                        <<setw(10)
                                        <<iplot[kk]
                                        <<setw(10)
                                        <<fplot[kk]
                                        <<setw(10)
                                        <<fplot_CN[kk]
                                        <<endl;
            rainfall <<setiosflags(ios::fixed)<<setw(10)
                                        <<time[k+1]
                                        <<setw(10)
                                        <<iplot[++kk]
                                        <<setw(10)
                                        <<fplot[kk]
                                        <<setw(10)
                                        <<fplot_CN[kk]
                                        <<endl;
            kk++;
    }
          m_dlg.m_CN24hr=CN;
          m_SCSCN=CN;
          m_dlg.m_Q24excess=Q24;
          m_SCSQ24=Q24;
          m_dlg.m_Smaxret=S;
          m_SCSS=S;
          m_dlg.m_F24infilt=F24;
          m_SCSF24=F24;
          m_dlg.m_F288infilt=F[288];
          m_GAF24=F[288];
          m_dlg.m_Sminus=Sminus;
          m_dlg.m_Splus=Splus;
          m_dlg.m_S1=S1;
          m_dlg.m_S2=S2;
//        m_dlg.DoModal();                    //open SCS CN output window
```

```
	m_finish="Change parameters & restart";
	UpdateData(FALSE);
 }
	raindist.close();
	infiltrate.close();
	rainfall.close();
}

void CGreenADlg::OnReenterButton()
{
	// TODO: Add your control notification handler code here
	m_Infile=Infile1;
	m_finish=" ";
	UpdateData(FALSE);
}

void CGreenADlg::OnChgOutfileButton()
{
	// TODO: Add your control notification handler code here
	m_Outfile=Outfile1;
	m_finish=" ";
	UpdateData(FALSE);
}

void CGreenADlg::OnRfoutfileDefaultButton()
{
	// TODO: Add your control notification handler code here
	m_rfoutfile=Outfile2;
	m_finish=" ";
	UpdateData(FALSE);
}
```

<greenampt.cpp>

```
//greenampt.cpp
//version 2.21, 5/20/2001, 11:30 a.m.
//greenampt infiltration for the SCS TypeII rainfall distribution
//using 30 min. time increments in rainfall input, and 5 minute computational
//increments. The Green-Ampt infiltration at 24 hours is used to calculate an
//equivalent curve number CN, using the standard initial abstraction Ia=0.2S.
//The computational core of this program was copied from the MFCinfilt-
//CGreenADlg.cpp program at the version 3.2, 5/10/01 level. It produces 29
//pairs of CN versus G-A K values for 9 storm depths, ranging from 4 cm to
//36 cm in 4 cm increments. The G-A parameter delta theta is entered manually
//for each execution from the console window as a floating point number,
//for one of the 10 possible soil texture classes.
//detheta is defined as: detheta=(total porosity)-(initial moisture content).
//29 values of psi are calculated ranging in equal log-increments from the low 1
//standard deviation range of psi to the high value, for the particular soil
//texture class. Corresponding K values are computed from the linear
//relationship.
#include <iostream.h>
#include <cmath>
#include <fstream.h>
#include <iomanip.h>
#include <ios.h>
void main()
{
        double P[9],K,KK[9][29],CN[9][29],logK[9][29];
        double i[288],f[289],F[289],fpot[289],dt,psi,dtheta,logpsi,ci[5][49];
        double F1,F2,DF,Fpond[289],dtp,R,Q24,CNc,cd[48],Q[289];
        double cd5[288],t,I[289],time[289],S,S1,S2,Sminus,Splus;
        double tpond[289],fpond[289],lowpsi,highpsi,lowLogpsi,highLogpsi,incLogpsi;
        long int m,n,k,kk,LK,ierr;
        dt=1.0/12.0;                                        //set dt=1/12 hr (5 min. intervals).
        m=3;            //load storm dist. number from radio button.
                                // 0=uniform, 1=TypeI, 2=TypeIA, 3=TypeII, 4=TypeIII
        //open input file for 24 hourly values of rainfall intensity:
        ifstream raindist("c:\\cprograms\\SCSII_uniform_rf_dist.dat",ios::in);
        if(raindist.fail()) cout<<"file SCSII_uniform_rf_dist.dat open failed"<<endl;
        //open output file for 24 hourly values of infiltration rate:
        ofstream greenampt("c:\\cprograms\\greenampt.dat",ios::out);
        if(greenampt.fail()) cout<<"file greenampt.dat open failed"<<endl;
        ierr=0;
        do                                  //enter value of dtheta from the console window and
error check it.
        {
        cout <<"Enter the value of dtheta as a floating point number" << endl
                <<"in the range of 0.0 < dtheta < total porosity <1.0 :" << endl;
        cin >> dtheta;
//      dtheta=0.40;                                        //set dtheta = soil texture class
value.
                if((dtheta<0.0)||(dtheta>=1.0))
                {
                        ierr=1;
                        cout <<"dtheta is out of the range 0.0 <= dtheta < 1.0, re-enter a valid value."
                                << endl;
                }
```

```
		else
		{
			ierr=0;
		}
	}
	while(ierr==1);
	cout <<"Enter the low and high psi 1 standard deviation values." << endl
			<<"type 2 floating point numbers separated by a space, then press Enter:"
			<< endl;
	cin >> lowpsi >> highpsi;
	lowLogpsi=log10(lowpsi);			//convert low and high 1-std range into log10
	highLogpsi=log10(highpsi);
	incLogpsi=(highLogpsi-lowLogpsi)/28.0;		//compute log10 psi increment on 29 values.
	R=2.54;						//enter inches to cm
conversion.
	for(n=0;n<49;n++)
	{
		//read in cumulative rf distributions, 0.5 hr increments.
		raindist >>t>>ci[0][n]>>ci[1][n]>>ci[2][n]>>ci[3][n]>>ci[4][n];
		if(n>0)
		{
			cd[n-1]=ci[m][n]-ci[m][n-1];	//compute differential accumlation.
			for(k=0;k<6;k++)
			{
				cd5[kk]=cd[n-1]/6.0;	//compute 5 min. accumulations.
				kk++;
			}
		}
	}
 for(m=0;m<9;m++)					//storm depth loop. 9 storms: 4-36cm depth
 {
		P[m]=4.0+4.0*m;				//load current storm depth, cm.
		for(k=0;k<288;k++)
		{
			i[k]=P[m]*cd5[k]/dt;		//load rainfall rate for storm depth, cm/hr.
		}
  for(LK=0;LK<=28;LK++)			//enter G-A K loop, compute 29 values from 3.1623 - 0.005
cm/hr.
  {
	logpsi=lowLogpsi+incLogpsi*LK;			//compute current logpsi value.
	psi=pow(10.0,logpsi);				//compute current psi value.
	logK[m][LK]=(1.0177-logpsi)/0.3266;		//compute log10 of K based on Lena's linear
fit.
	KK[m][LK]=pow(10.0,logK[m][LK]);		//compute current K value.
	K=KK[m][LK];					//load current K value.
	cout <<m<<" "<<LK<<" "<<logpsi<<" "<<psi<<" "<<logK[m][LK]<<" "<<K<<endl;
	fpot[0]=99999.;				//assign a large initial potential infiltration.
	F[0]=0.0;					//assign initial accumulated infiltration.
	Q[0]=0.0;					//assign initial accumulated runoff.
	I[0]=0.0;				//assign initial accumulated rainfall.
	f[0]=i[0];					//set initial infiltration rate = rainfall rate.
	time[0]=0.0;				//initialize the time counter.
	Fpond[0]=Fpond[288]=0.0;		//set intial and final ponding parameters.
	tpond[0]=tpond[288]=0.0;
	fpond[0]=fpond[288]=0.0;
   for(n=0;n<288;n++)			//enter computational loop for infiltration at 5 min increments.
```

```
  {                                                          //total of 288 5-min. increments in 24 hour storm.
        time[n+1]=(n+1)*dt;
        if(fpot[n]<=i[n])
        {
              //ponding throughout the interval:
              Fpond[n]=F[n];                    //store accumulated infiltration at ponding.
              tpond[n]=time[n];                 //store time at ponding.
              fpond[n]=f[n];                    //store infiltration rate at ponding.
              //iterate to find F[n+1]:
              F1=F[n]+K*dt;                                       //set initial value.
              do
              {
                    F2=F[n]+K*dt+psi*dtheta*log((F1+psi*dtheta)/(F[n]+psi*dtheta));
                    DF=fabs(F2-F1);
                    F1=F2;
              }
              while(DF>0.000001);
              F[n+1]=F2;                                          //compute new infiltration depth.
              fpot[n+1]=K*(psi*dtheta/F[n+1]+1);
        }
        else
        {
              //calculate tentative values of F[n+1] & fpot[n+1]
              F[n+1]=F[n]+i[n]*dt;
              fpot[n+1]=K*(psi*dtheta/F[n+1]+1);
              if(fpot[n+1]<=i[n])
              {
                    //ponding occurs during interval
                    Fpond[n]=K*psi*dtheta/(i[n]-K);            //compute F at ponding point.
                    dtp=(Fpond[n]-F[n])/i[n];                  //compute ponding delta t.
                    tpond[n]=time[n]+dtp;                            //compute time of ponding.
                    fpond[n]=i[n];                                   //set infiltration rate at ponding.
                    //iterate to find F[n+1]:
                    F1=Fpond[n]+K*(dt-dtp);                    //set initial value.
                    do
                    {
                          F2=Fpond[n]+K*(dt-dtp)+psi*dtheta*log((F1+psi*dtheta)/(Fpond[n]+psi*dtheta));
                          DF=fabs(F2-F1);
                          F1=F2;
                    }
                    while(DF>0.000001);
                    F[n+1]=F2;                                       //store new infiltration depth.
              }
              else
              {
                    //no ponding during interval
                    Fpond[n]=0.0;                              //reset Fpond to zero for no ponding.
                    tpond[n]=0.0;                              //reset tpond to zero for no ponding.
```

```
                        fpond[n]=0.0;                           //reset fpond to zero for no
ponding.
                        F[n+1]=F[n]+i[n]*dt;            //compute new infiltration depth.
                }
        }
        f[n+1]=K*(psi*dtheta/F[n+1]+1);         //compute instantaneous potential infiltration rate.
        if(f[n+1]>=i[n])f[n+1]=i[n];            //assign actual infiltration rate at n+1.
        I[n+1]=i[n]*dt+I[n];                            //compute accumulated rainfall.
        Q[n+1]=I[n+1]-F[n+1];                                   //compute accumulated runoff.
        if(Q[n+1]<0.0)Q[n+1]=0.0;
  }                                                                     //end of for loop, 5 min
computational increments.
  Q24=P[m]-F[288];                                              //compute 24 hour runoff depth
  if(Q24<0.000001)Q24=0.0;
  S1=0.4*P[m]+0.8*Q24;                                  //begin computation of S and CN:
  S2=pow((0.4*P[m]+0.8*Q24),2.0)-0.16*(P[m]*P[m]-Q24*P[m]);
  if(S2<0.0)
  {
        S=9999.0;
        CNc=9999.0;
        Splus=S1;
        Sminus=S2;
  }
  else
  {
        Splus=(S1+sqrt(S2))/0.08;
        if(Splus<0.000001)Splus=0.0;
        Sminus=(S1-sqrt(S2))/0.08;
        if(Sminus<0.000001)Sminus=0.0;
        if((Sminus>=0.0)&&(P[m]-Q24-0.2*Sminus>=0.0))
        {
                S=Sminus;
        }
        else if((Splus>=0.0)&&(P[m]-Q24-0.2*Splus>=0.0))
        {
                S=Splus;
        }
        else
        {
                S=99999.0;
                CNc=99999.0;
        }
        if(S<99998.0)
        {
        CNc=(1000.0*R)/(S+10.0*R);              //calculate current value of CN.
        if(CNc<0.00001)CNc=0.0;
        }
  }
   CN[m][LK]=CNc;                                       //load calculated CN value.
  }
 }
 for(LK=0;LK<=28;LK++)                          //begin output of data according to format listed at
 {                                                              //beginning of this C++ listing.
        for(m=0;m<9;m++)
        {
                greenampt       <<setiosflags(ios::fixed)
```

```
                                        <<setw(12)
                                        <<CN[m][LK]
                                        <<setw(12)
                                        <<KK[m][LK];
      }
      greenampt      <<endl;
 }
     raindist.close();                  //close rainfall distribution input file.
     greenampt.close();                      //close CN versus K output file.
}
```

<3_SCS_Unit_Hydrograph.m>

```
%%% UNIT HYDROGRAPHS DEVELOPMENT and %%%%%
%%% AVERAGE CATCHMENT SLOPE CALCULATION  3_SCS_Unit_Hydrograph.m
%%% Program is written to calculate three durations unit hydrograpths from the SCS dimensionless unit
and to interpolate those hydrograpths with interval of 5 min.
%%% 03.20.01
  CN=[50:5:95];             % CN = curve number
  hydl=500+sqrt(500^2+500^2); % hydl = hydraulic length in meters
  A=1;                      % A = area of watershed in sq.km

                           % tr = unit hydrograph duration in hours
                           % tp = time to peak of unit hydrograph
                           % Y = average catchment land slope in
                                meters per meters
                           % qp = peak discharge in cms

  n=[1:1:3];
  for n=1

     tr1=0.0833333;
     tp1=tr1*5;

     for i=1:1:10

        Y1(i)=(hydl^1.6)*((2540-22.86.*CN(i))^1.4)/((45*n/120).^2)/(14104^2)/(CN(i)^1.4);

     end

     qp1=tp1.\(2.08*A);
     DUHt=[0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0 2.1 2.2 2.3 2.4
2.5 2.6 2.7 2.8 2.9 3.0 3.1 3.2 3.3 3.4 3.5 3.6 3.7 3.8 3.9 4.0 4.1 4.2 4.3 4.4 4.5 4.6 4.7 4.8 4.9 5.0 5.1 5.2
5.3 5.4 5.5 5.6 5.7 5.8 5.9 6.0 6.2 6.4 6.6 6.8 7.0 7.5 8.0 8.5 9.0 10.0 11.0 12.0 13.0 14.0 15.0];
     DUHd=[0 0.03 0.1 0.19 0.31 0.47 0.66 0.82 0.93 0.99 1 0.99 0.93 0.86 0.78 0.68 0.56 0.46 0.39 0.33
0.28 0.2435 0.207 0.177 0.147 0.127 0.107 0.092 0.077 0.066 0.055 0.0475 0.040 0.0345 0.029 0.025
0.021 0.018 0.015 0.013 0.011 0.0105 0.01 0.0085 0.007 0.005 0.003 0.00225 0.0015 0.00075 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0  0 0 0 0 0 0 0 0 0 0 0];

     x1=DUHt*tp1;
     y1=DUHd*qp1;
     xi1=0:0.0833333:6.25;
     yi1=interp1(x1,y1,xi1,'spline');
  end

  for n=2
     tr2=0.1666667;
     tp2=tr2*5;
     for i=1:1:10

        Y2(i)=(hydl^1.6)*((2540-22.86.*CN(i))^1.4)/((45*n/120).^2)/(14104^2)/(CN(i)^1.4);

     end

     qp2=tp2.\(2.08*A);
```

```
    DUHt=[0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0 2.1 2.2 2.3 2.4
2.5 2.6 2.7 2.8 2.9 3.0 3.1 3.2 3.3 3.4 3.5 3.6 3.7 3.8 3.9 4.0 4.1 4.2 4.3 4.4 4.5 4.6 4.7 4.8 4.9 5.0 5.1 5.2
5.3 5.4 5.5 5.6 5.7 5.8 5.9 6.0 6.2 6.4 6.6 6.8 7.0 7.5 8.0 8.5 9.0 10.0 11.0 12.0 13.0 14.0 15.0];
    DUHd=[0 0.03 0.1 0.19 0.31 0.47 0.66 0.82 0.93 0.99 1 0.99 0.93 0.86 0.78 0.68 0.56 0.46 0.39 0.33
0.28 0.2435 0.207 0.177 0.147 0.127 0.107 0.092 0.077 0.066 0.055 0.0475 0.040 0.0345 0.029 0.025
0.021 0.018 0.015 0.013 0.011 0.0105 0.01 0.0085 0.007 0.005 0.003 0.00225 0.0015 0.00075 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0  0 0 0 0 0 0 0 0 0 0 0];

    x2=DUHt*tp2;
    y2=DUHd*qp2;
    xi2=0:0.0833333:6.25;
    yi2=interp1(x2,y2,xi2,'spline');
  end
  for n=3
    tr3=0.25;
    tp3=tr3*5;
    for i=1:1:10

      Y3(i)=(hydl^1.6)*((2540-22.86.*CN(i))^1.4)/((45*n/120).^2)/(14104^2)/(CN(i)^1.4);

    end

    qp3=tp3.\(2.08*A);
    DUHt=[0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0 2.1 2.2 2.3 2.4
2.5 2.6 2.7 2.8 2.9 3.0 3.1 3.2 3.3 3.4 3.5 3.6 3.7 3.8 3.9 4.0 4.1 4.2 4.3 4.4 4.5 4.6 4.7 4.8 4.9 5.0 5.1 5.2
5.3 5.4 5.5 5.6 5.7 5.8 5.9 6.0 6.2 6.4 6.6 6.8 7.0 7.5 8.0 8.5 9.0 10.0 11.0 12.0 13.0 14.0 15.0];
    DUHd=[0 0.03 0.1 0.19 0.31 0.47 0.66 0.82 0.93 0.99 1 0.99 0.93 0.86 0.78 0.68 0.56 0.46 0.39 0.33
0.28 0.2435 0.207 0.177 0.147 0.127 0.107 0.092 0.077 0.066 0.055 0.0475 0.040 0.0345 0.029 0.025
0.021 0.018 0.015 0.013 0.011 0.0105 0.01 0.0085 0.007 0.005 0.003 0.00225 0.0015 0.00075 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0  0 0 0 0 0 0 0 0 0 0 0];

    x3=DUHt*tp3;
    y3=DUHd*qp3;
    xi3=0:0.0833333:6.25;
    yi3=interp1(x3,y3,xi3,'spline');
  end


 fid=fopen('hyrograph.txt','w');
 fprintf(' %6.6f  \n',xi3);
 fprintf(fid,'%2.5f\n',y1);

 status=fclose(fid);

figure(1);
plot(xi1,yi1,'red',x1,y1,'blue')
grid on;
xlabel('time')
ylabel('discharge')

figure(2);
plot(xi2,yi2,'red',x2,y2,'blue')
grid on;
xlabel('time')
ylabel('discharge')
```

```
figure(3);
plot(xi3,yi3,'red',x3,y3,'blue')
grid on;
xlabel('time')
ylabel('discharge')
```

<UH_runoff_SCS.m>

```
%UH_runoff_SCS.m  Version 1.10, 5/27/01
%
%Convolutes 3 SCS Unit Hydrographs with rainfall excess generated
%by the <MFCinfilt\CGreenADlg.cpp> Windows program, with default output
%file: <infilt_output.dat>.  This latter file is renamed in a format
%<infilt_P8_CN60.dat> to identify the rainfall depth (8 cm in this
%example) and the SCS CN (60 in this example)for a corresponding
%unique set of Green-Ampt parameters, consisting of total porosity,
%initial soil moisture content, and hydraulic conductivity K. The
%wetting front capillary pressure, psi, can be determined via a log-
%log relationship with K, or by separate entry into the windows
%program. Each run of the windows program generates 15 columns of
%infiltration and runoff data for both the Green-Ampt model and
%an equivalent SCS CN infiltration model, matched by equating the
%24 hr runoff depth accumulations, Q and Q_CN. Each column of data
%in the output file has 289 data values, at 5 min intervals over
%24 hours. Runoff accumulations Q and Q_CN are selected from their
%respective locations in the input file for used on convoluting
%separate runoff hydrographs from each of the 3 UH's.
%
%Open the <infilt_output.dat> file version for this storm event:

infilt = fopen('c:\cprograms\GA_CN_data\infilt_P8_CN60.dat','r');

%Read in the entire output file (15 columns x 289 length);
%store it in matrix "datin [15 rows, 289 columns]"

inmat = fscanf(infilt,'%g',[15 289]);
status1 = fclose(infilt);              %Close the input file.

%Transpose the input matrix so that it has the correct [289,15] format.

inmat = inmat';

%Open the SCS Unit Hydrograph file containing tr=5,10,15 min. UH's
%Note that this input file has no leading time column, just the
%3 columns storing 76 values for each UH.

UHpt = fopen('c:\cprograms\GA_CN_data\3UH_Lena_01.txt','r');

%Read in UH's in column-row format (3 rows of 76 columns);
%which is required due to limitations of the fscanf function in
%reading text files; requiring sequential reading of each line
%in the file from top to bottom.

UHall = fscanf(UHpt,'%g',[3 76]);
status2 = fclose(UHpt);                %Close the input file.

%Transpose the input matrix so that it has the correct [76,3] format.

UHall = UHall';
```

```
%Load vectors Q_GA and Q_CN from the inmat matrix:

Q_GA = inmat(1:289,5);
Q_CN = inmat(1:289,12);

%Convert accumulated rainfall excess Q_GA and Q_CN into 5 min.
%accumulations. Store GA in column 1, and CN in column 2, of Q5.
%<note that Q5 will have 288 values>
xstring = 'executing....please wait';   %set execution notice.
for I=1:289
   if I > 1
      Q5(I-1,1) = Q_GA(I)-Q_GA(I-1);
      Q5(I-1,2) = Q_CN(I)-Q_CN(I-1);
   end
end
dt = 5.0;                      %load time increment in minutes.
for model=1:2                  %Select G-A <1> and then CN <2> models:
   for n=1:3                   %load no. of rainfall bars for each tr:
      ict=0;                   %zero time increment counter.
      for I=1:(288/n)          %loop through the n*5 min.
accum.'s.
        Qsum=0.0;              %zero summation variable.
        for m = 1:n            %sum rainfall excess in each tr
bar:
           ict=ict+1;          %index time counter.
           Qsum=Qsum+Q5(ict,model); %sum R.F. excess in each tr
bar.
        end
        Qtr(I,n,model)=Qsum;   %store R.F. excess
     end
  end
end
%Enter convolution loops to Convolute the 3 UH's with the R.F. excess.
for model=1:2                  %Select GA <1> and then CN <2> models:
   for n=1:3                   %Select 5, 10, and then 15 min. UH
loop:
      disp(xstring)            %print "executing" to the screen.
      M=288/n;                 %Compute number of rainfall bars.
      %load the rainfall bars with the accumulations in each one:
      for I=1:(363-(n-1))      %Enter hydrograph ordinate loop:
         Qsum=0.0;             %Zero ordinate sumation variable.
         for m=1:M             %Enter ordinate summation loop.
            %Add next term to the ordinate summation:
            Uind=I-(m-1)*n; %compute UH ordinate index.
            if (0 < Uind) & (Uind <= 76)
               Qsum=Qsum+Qtr(m,n,model)*UHall(Uind,n);
            end
         end
         Qhyd(I,n,model)=Qsum;   %store discharge, m^3/s.
      end
   end
end
%Enter nested loops to compute integrated runoff depth for checking:
for model=1:2
   for n=1:3
      ROsum=0.0;               %zero depth summation variable.
```

```
        for I=1:363
            ROsum=ROsum+Qhyd(I,n,model)*0.03;   %add depth, cm, in
delta t.
        end
        RO(n,model)=ROsum;      %store total runoff depth, cm.
    end
end
%Write out the hydrographs to an ASCII data file:
outpt = fopen('c:\cprograms\GA_CN_data\P8_CN60_runoff.dat','w');
for I=1:363
    time=(I-1)*(5.0/60.0);
    fprintf(outpt,'%10.6f ',time);
    for model=1:2
        for n=1:3
            fprintf(outpt,'%10.6f ',Qhyd(I,n,model));
        end
    end
    fprintf(outpt,'\n');
end
status3 = fclose(outpt);
```

APPENDIX D

EXAMPLE

In order to provide an example of the use of the procedure, developed by the present project, the following instance of deriving the Green-Ampt parameters from the SCS Curve Numbers was created. The example is based on data that were used and determined during the investigation:

A watershed of an area of 1 km^2 has CN=70 and a time of concentration, T_c= 75 min.

The 24-hr rainfall (P) of 16 cm of depth and Type II standard rainfall distribution.

The soil is Silt Loam and hydrologic soil group B.

<u>Determination of the Green-Ampt parameters and calculation of 24-hr infiltration:</u>

1. Determine the hydraulic conductivity value (K) from Figure 4.6 for corresponding Curve Number = 70 and rainfall depth, P = 16 cm.

   K = 0.394 cm/hr

2. Calculate the wetting front capillary pressure (ψ) by equation 4.1:

   $\log\psi$ = -0.3266*$\log K$+1.0177

   ψ =14.119 cm

3. Obtain the value of the change in moisture content ($\Delta\theta$) from Table 4.4 for Silt Loam soil texture class.

   $\Delta\theta$ = 0.169 cm^3/cm^3

4. Compute the accumulated infiltration and infiltration rates by the Green-Ampt model's equations.

   Accumulated infiltration equation:

$$F - F_p - \psi\Delta\theta \ln\left(\frac{\psi\Delta\theta + F}{\psi\Delta\theta + F_p}\right) = K(t - t_p)$$

Infiltration rate:

$$f = K(\frac{\psi\Delta\theta}{F} + 1)$$

where: t_p- ponding time

$$t_p = \frac{K\psi\Delta\theta}{i(i-K)}$$

where: i- rainfall rate

The accumulated infiltration (F) is calculated by the “GreenADlg.cpp” computer program (Appendix C) and presented in Figure B.6 (Appendix B).

Runoff distribution (hydrograph) is calculated using the SCS runoff hydrograph development procedure and available in Figure A.17 (Appendix A).

VITA

Elena Viktorovna Brevnova was born May 14, 1966 in the town of Kalinovo, Russia. In 1994, she graduated from the Saint Petersburg Technical University with a Master's Degree in Chemical Engineering. She came to the United States in 1995, and in 1998 began a program of studies in Civil Engineering, which has culminated in the present thesis.